

SEDIMENTARY PETROGRAPHY

*With Special Reference to Petrographic Methods of
Correlation of Strata, Petroleum Technology
and other Economic Applications of Geology*

VOLUME II
PRINCIPLES AND APPLICATIONS

by

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H.B.M.

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CHAPTER I

DIAGNOSTIC PROPERTIES OF SEDIMENTARY ROCK MINERALS

IN this chapter is a summary of the principal properties of mineral species likely to be found in sedimentary rocks. Excluding many rare alluvial minerals and those essentially recent products of local environments, the data will be found complete for all normal diagnostic work.

Obviously, of a total of well over eight thousand different minerals now known to science, a large percentage is capable of occurring in sedimentary deposits, given relevant parent-rocks in the region concerned; exhaustive treatment would thus demand an unwieldy treatise on detrital mineralogy which every consideration renders impracticable. Experience, however, shows that a comparatively small proportion of minerals is identifiable in sedimentary rocks of *any geological age* and that it is only when recent, especially alluvial, deposits are studied that the list can be indefinitely expanded; even in the latter case, it is in some respects surprising how many species fail to survive and study of the records of alluvial minerals from all over the world soon reveals the restriction of species imposed by rapidly destructive chemical and mechanical forces¹.

The detailed information given in this chapter should in itself be sufficient for determining a particular mineral, but a working knowledge of crystallography—a *sine qua non* to this particular study—is assumed throughout. As will be seen, the information is arranged under stereotyped headings, *viz.* chemical composition, system of crystallization, habit, structure, cleavage, fracture, hardness, specific gravity, lustre, colour, magnetic and electrostatic properties, optical properties, characters in sediments, occurrence, later records², possible sources of derivation, remarks and special references to recorded occurrences or to general literature.

Chemical Composition. Minerals vary widely in composition, especially the more complex silicates. Except in simple cases,

formulae given are empirical and designed to indicate elements normally concerned in the composition of the species rather than precise chemical constitution. In a majority of cases the formulae quoted are those cited by E. S. Larsen and H. Berman¹.

System of Crystallization. With few exceptions, e.g. pseudo-hexagonal forms in the orthorhombic system and certain doubtful monoclinic and triclinic species indicated with a (?), the crystal systems quoted are definite.

Habit. Under this heading is given in order of occurrence the common form of the crystallized mineral which may be expected, *ceteris paribus*, to determine the average appearance of the detrital grain. The notation (Millerian) of the crystal faces to be anticipated is given, while twinning, if any, is conventionally defined. It should be remarked in the latter connexion that, while many minerals are prone to exhibit twinning in their native environment, such developments, save for example the feldspar group, seem relatively seldom to persist in sediments.

Structure. This has reference to the tendency of the native mineral to occur either as crystalline or in particularly characteristic forms. The former may be expected to predominate in sediments.

Cleavage. The principal directions of cleavage are quoted in order of perfection. The property is a very important one with detrital minerals, in that in a majority of cases it tends to determine the relevant crystal face presented by the sedimentary rock species. Parting planes are also quoted under this heading.

Fracture. This again has reference to the mineral in its native state and from the standpoint of its detrital derivative is a guide to what must be anticipated as regards shape.

Hardness. The values quoted are in accordance with Mohs' scale.

Specific Gravity. With many minerals this is a variable function depending on composition. Where one value alone is quoted it represents the average of several records. Where variation limits are persistent in the records, limiting values are given.

Lustre. This property has reference not only to the appearance of the mineral in its native state but also in the detrital form as

viewed normally by dark ground illumination under the microscope. In certain cases the reaction of the mineral to reflected polarized light is given.

Colour. Colour depends to a large extent on composition and may be expected to vary accordingly. Colours quoted are in order of frequency and represent the tints to be anticipated from observation of the species. Generally the colour of detrital grains is paler than that of the parent mineral in bulk. The words 'transparent', 'translucent' and 'opaque' are added to indicate the common degree of visibility 'through' the grain or otherwise when viewed under the microscope.

Magnetic Properties. Detrital minerals are designated as 'strongly', 'moderately', 'weakly' or 'non-magnetic' (as the case may be), according to the conventional tests as described in Vol. I, Chapter V, p. 194.

Electrostatic Properties. Detrital minerals are designated as 'good', 'moderate', 'weak' or 'non-conductors', according to the conventional tests as described in Vol. I, Chapter V, page 199.

Optical Properties. (a) *Refractive Index.* The values throughout this book are in general quoted from E. S. Larsen and H. Berman¹ and have been compared with other authors. They are qualified as follows:

< 1.600	..	..	..	..	low
> 1.600 and < 1.750	..	..	..	..	high
> 1.750	..	..	..	..	very high

In all cases extreme limits, determined by variable composition, have been avoided, the values given being those of the normal mineral.

(b) *Birefringence.* The value represents the normal arithmetic difference between the greater and the lesser R.I. figure. The qualification is according to E. S. Larsen and H. Berman². 'The birefringence is said to be weak if it is less than 0.010, moderate if between 0.010 and 0.025, strong if between 0.025 and 0.100, very strong if between 0.100 and 0.200, and extreme if greater than 0.200.'

(c) The other optical characters are given in logical order, e.g. isotropic, uniaxial or biaxial character, position of optic axial plane, acute bisectrix, etc. In a majority of cases these functions are quoted from A. N. Winchell³.

¹ *Op. cit.* ² *Op. cit.*, p. 16.

³ *Elements of Optical Mineralogy*, 3rd ed., Part 2 (Wiley, New York) 1933.

(d) Pleochroism where relevant is quoted in accordance with the generally recognized absorption scheme, qualified by the average colours noted for particular directions of light vibration.

(e) Anomalous optical properties where important are stated.

The data included in each case under 'Optical Properties' must only be considered as a working summary. For more detailed information the student should refer to the authors cited and also to the standard texts by J. D. Dana¹, J. P. Iddings² and A. N. Winchell³.

Characters in Sediments. This has reference to the particular interpretation of sedimentary rock minerals with which we are concerned here, *i.e.* the modifications undergone by such minerals during their transference from parent rock to sedimentary deposit, alternatively during their growth *in situ* in certain well defined environments. Under this heading are included those peculiar collective properties by which detrital minerals achieve individuality, by which in fact they are correctly diagnosed under the microscope. Detrital mineral variations are legion; only constant experience with them in all kinds of deposits from world-wide sources can bring real competence in their identification and interpretation. The data given represent in practically every case the average results of the author's examination of a large and varied selection of examples, reinforced where appropriate with references to published observations of other petrographers.

Occurrence. As far as possible the occurrences listed have reference to British sources and they are arranged in stratigraphical (ascending) order. In some cases, where the mineral is scarce in British sediments, but none the less important in foreign environments, certain overseas localities are given. In the latter connexion, as well as with the British records, individual authors are acknowledged, but in the case of some publications not easily available, one by P. G. H. Boswell⁴ is relevant, and to this the student is referred for more extensive records of occurrence.

Later Records. These supplement *Occurrence* as above and date from the 3rd edition of this book (1940) onwards.

Possible Sources of Derivation. Provenance is suggested in every case and is of obvious importance in comprehensive investigation

of a sediment. The parent rocks are noted in order of probability and the information given should aid palaeogeographical interpretations.

Remarks. Any special features to be expected concerning the mineral species, its varieties, its possible confirmation by chemical or other means, are noted under this heading.

References. References are to the *Occurrence* and *Later Records* as listed previously. In addition certain general references are given where minerals, either in their native state or detrital developments, have been the subjects of intensive research.

The following is a complete list of the minerals, detrital and authigenic (including varieties), described in this chapter. These are arranged according to their systems of crystallization. The subsequent text arrangement is alphabetical.

ISOMETRIC (CUBIC) SYSTEM

Allophane (?).	Palladium
Almandite (Garnet Group)	Periclase
Analcite (Zeolite Group)	Perovskite ¹
Andradite (Garnet Group)	Picotite (Spinel Group)
Ceylonite (<i>syn.</i> Pleonaste) (Spinel Group)	Platinum
Chromite (Spinel Group)	Pleonaste (<i>syn.</i> Ceylonite) (Spinel Group)
Diamond	Pyrite
Fluorite	Pyrope (Garnet Group)
Galena	Romeite
Garnet (see varieties)	Sodalite
Gold	Spessartite (Garnet Group)
Grossularite (Garnet Group)	Sphalerite (<i>syn.</i> Zinc Blende)
Halloysite	Spinel (Spinel Group)
Hercynite (Spinel Group)	Thorianite
Maghemite	Uraninite
Magnetite (Spinel Group)	Uvarovite (Garnet Group)
Melanite (Garnet Group)	

TETRAGONAL SYSTEM

Anatase (<i>syn.</i> Octahedrite)	Torbernite
Autunite	Vesuvianite (<i>syn.</i> Idocrase)
Cassiterite	Viluite (<i>var.</i> Vesuvianite)
Chalcopyrite	Xenotime
Rutile	Zircon
Scheelite	

¹ Pseudoisometric.

TRIGONAL (RHOMBOHEDRAL) SYSTEM

Ankerite	Magnesite
Benitoite	Menaccanite (<i>syn.</i> Ilmenite)
Calcite	Phenacite
Corundum	Quartz
Dolomite	Ruby (<i>var.</i> Corundum)
Eudialite	Sapphire (<i>var.</i> Corundum)
Graphite	Siderite
Hematite	Tourmaline
Ilmenite (<i>syn.</i> Menaccanite)	

HEXAGONAL SYSTEM

Apatite	Molybdenite
Beryl	Nepheline
Cinnabar	Pyrrhotite
Iridosmine	

ORTHORHOMBIC SYSTEM

Andalusite	Fayalite (Olivine Group)
Anhydrite	Goethite ³
Aragonite	Humite (Humite Group)
Astrophyllite	Hypersthene (Pyroxene Group)
Barite	Iddingsite
Beidellite (Montmorillonite-Beidellite Series) ¹	Lawsonite
Boehmite	Marcasite
Bronzite (<i>var.</i> Enstatite) (Pyroxene Group)	Montmorillonite (Montmorillonite-Beidellite Series)
Brookite	Olivine (<i>syn.</i> Chrysolite) (Olivine Group)
Carpholite	Pseudobrookite
Celestite	Pyrophyllite
Chiastolite (<i>var.</i> Andalusite)	Sillimanite
Chrysoberyl	Staurolite
Chrysolite (<i>syn.</i> Olivine) (Olivine Group)	Steatite (<i>syn.</i> Talc) ⁴
Chrysotile ²	Strontianite
Columbite-Tantalite	Sulphur
Cordierite	Talc (<i>syn.</i> Steatite) ⁴
Diaspore	Thulite (<i>var.</i> Zoisite) (Epidote Group)
Dumortierite	Topaz
Enstatite (Pyroxene Group)	Zoisite (Epidote Group)
Eschynite	

¹ Pseudohexagonal.² Dimorphous with antigorite (chlorite group), *q.v.*³ In some instances may be tetragonal. Also amorphous.⁴ Pseudohexagonal.

MONOCLINIC SYSTEM

Actinolite (Amphibole Group)	Hornblende (Amphibole Group)
Aegirine (Pyroxene Group)	Kaolinite (with Anauxite)
Allanite (<i>syn.</i> Orthite)	Kunzite (Spodumene) (Pyroxene Group)
Antigorite (Chlorite Group)	Lepidolite (Mica Group)
Arfvedsonite (Amphibole Group)	Lepidomelane (Mica Group)
Arsenopyrite	Monazite
Augite (Pyroxene Group)	Muscovite (Mica Group)
Baddelyite	Nacrite
Barkevicite (Amphibole Group)	Nephrite (<i>syn.</i> Jade, <i>var.</i> Tremolite or Actinolite) (Amphibole Group)
Basaltine (Basaltic Hornblende) (Amphibole Group)	Nontronite (Montmorillonite-Beidellite Series)
Bastite (<i>var.</i> Antigorite) (Chlorite Group)	Omphacite (<i>var.</i> Diopside) (Pyroxene Group)
Biotite (Mica Group)	Orthite (<i>syn.</i> Allanite)
Chamosite	Orthoclase (Felspar Group)
Chlorite (Chlorite Group)	Ottrelite (Chloritoid-Ottrelite Group)
Chloritoid (Chloritoid-Ottrelite Group) ¹	Penninite (Chlorite Group)
Clinocllore (Chlorite Group)	Phlogopite (Mica Group)
Clinozoisite (Epidote Group)	Piedmontite (Epidote Group)
Crossite	Pumpellyite
Cymatolite (<i>syn.</i> Spodumene)	Riebeckite (Amphibole Group)
Delessite (Chlorite Group)	Sanidine (Orthoclase Group)
Diallage (<i>var.</i> Diopside) (Pyroxene Group)	Selenite (<i>cryst.</i>) (Gypsum)
Dickite (Kaolin Group)	Serpentine (Serpentine Group)
Diopside (Pyroxene Group)	Sphene (<i>syn.</i> Titanite)
Epidote (Epidote Group)	Spodumene (Pyroxene Group)
Euclase	Steatite (<i>syn.</i> Talc) ²
Fuchsite	Stilpnomelane ³
Gadolinite	Talc (<i>syn.</i> Steatite) ²
Gastaldite	Thuringite
Gibbsite (<i>syn.</i> Hydrargillite)	Titanite (<i>syn.</i> Sphene)
Glaucconite	Tremolite (Amphibole Group)
Glaucophane (Amphibole Group)	Triphane (<i>syn.</i> Spodumene)
Gypsum	Wolframite
Heulandite	Wollastonite
Hiddenite (<i>var.</i> Spodumene) (Pyroxene Group)	

¹ Monoclinic (pseudo-hexagonal) or may be triclinic.² ? Orthorhombic.³ ? Monoclinic.

TRICLINIC (ANORTHIC) SYSTEM

Albite (Plagioclase Felspar Group)	Enigmatite
Andesine (Plagioclase Felspar Group)	Eudialite
Anorthite (Plagioclase Felspar Group)	Kyanite
Anorthoclase (Felspar Group)	Labradorite (Plagioclase Felspar Group)
Axinite	Microcline (Felspar Group)
Bytownite (Plagioclase Felspar Group)	Oligoclase (Plagioclase Felspar Group)
	Plagioclase (see varieties)

AMORPHOUS MINERALS

Agate	Jasper
Amber	Leucoxene
Chalcedony	Limonite
Chert	Opal (<i>syn.</i> Hyalite)
Collophane	Phosphorite
Flint	Psilomelane
Goethite	Pyrolusite
Halloysite	

Attention is directed to the various tables of mineral constants (Appendices I–VIII) by which it is hoped considerable help will be afforded the student in rapidly checking a species of which he is doubtful, once he has ascertained certain specific optical or other physical properties. Mineral associations and significance of ‘index species’ are not dealt with in this chapter but receive full discussion in Chapter VI, which will be found to contain a great deal of supplementary information of use where diagnosis of one or more mineral species may lead to anticipation of paragenetic species likely to occur in the same sample, hence to sound conclusions regarding source of origin of the sediment in which they occur.

In the following pages, Figs. 1–36 illustrate the common crystal forms of the seven systems, with Millerian notations, and examples of relevant mineral species. :

ISOMETRIC SYSTEM

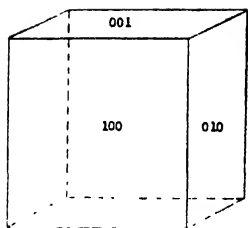


FIG. 1. Cube (a).
e.g. Thorianite.

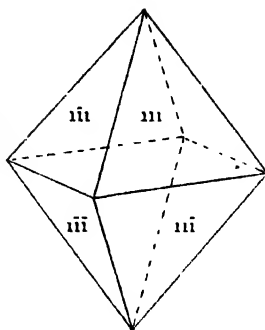


FIG. 2. Octahedron (o)
e.g. Gold, Magnetite, Spinel.

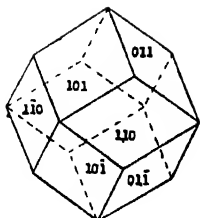


FIG. 3. Dodecahedron
(d).
e.g. Gold, Garnet.

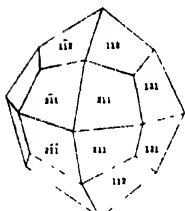


FIG. 4. Trapezohe-
dron or Icositetrahe-
dron (n).
e.g. Garnet.

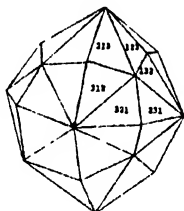


FIG. 5. Hexoctahe-
dron (s).
e.g. Diamond.

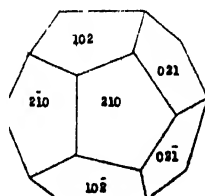


FIG. 6. Pyritohedron
(c).
e.g. Pyrite.

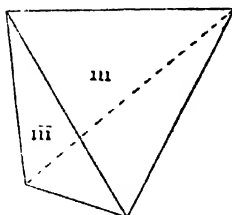


FIG. 7. Tetrahedron (o).

TETRAGONAL SYSTEM

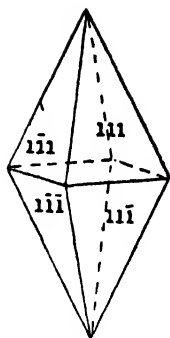


FIG. 8. Pyramid
(p).
(First Order.)
e.g. Anatase.

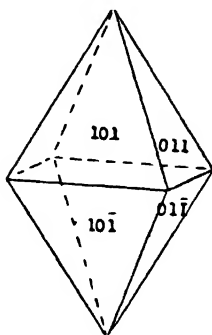


FIG. 9. Pyramid (e).
(Second Order.)

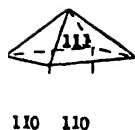


FIG. 10. Prism
(m) & Pyramid
(p).
(First Order.)
e.g. Zircon.

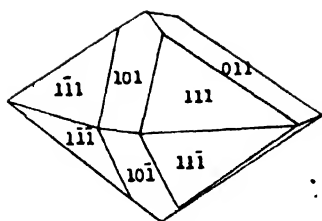


FIG. 11. Pyramids (p) and (e).
(First and Second Order.)
e.g. Cassiterite.
(After Dana.)

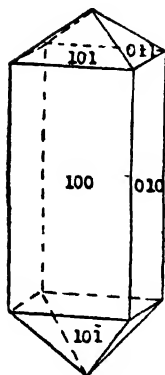


FIG. 12. Prism (a)
and Pyramid (e).
(Second Order.)
e.g. Zircon (in combination with other forms.)

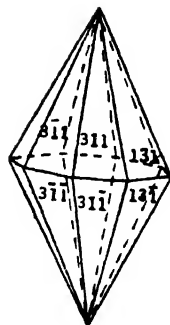


FIG. 13. Ditetragonal Pyramid (x).
e.g. Zircon (in combination with other forms; not found alone).

DIAGNOSTIC PROPERTIES

HEXAGONAL SYSTEM

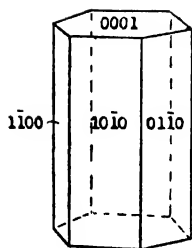


FIG. 14. Prism (m).
(First Order)
e.g. Beryl (in combination with other forms).

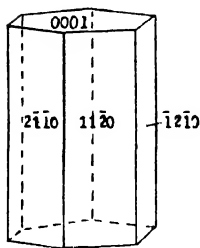


FIG. 15. Prism (a).
(Second Order.)

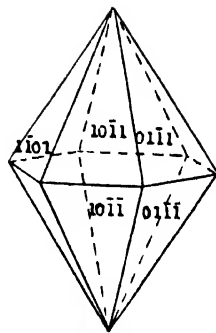


FIG. 16. Pyramid (p).
(First Order.)
e.g. Beryl (in combination with other forms).

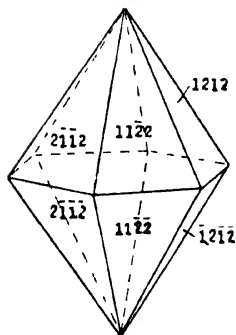


FIG. 17. Pyramid (s).
(Second Order.)
e.g. Beryl (in combination with other forms).

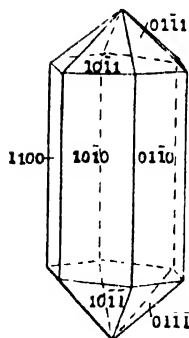


FIG. 18. Prism (m) and Pyramid (p).
(First Order.)
e.g. Beryl, Apatite. (Often with other forms.) (After Dana.)

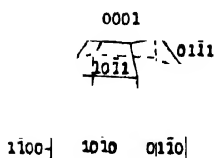


FIG. 19. Prism (m) and Pyramid (p) with base (c).
e.g. Apatite. (After Dana.)

RHOMBOHEDRAL SYSTEM

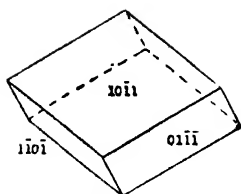


FIG. 20. Rhombohedron
(r)
(positive).

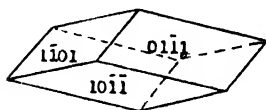


FIG. 21. Rhombohedron
(r)
(negative).

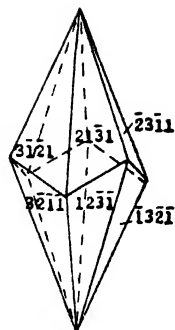


FIG. 22. Scalenohedron
(v).

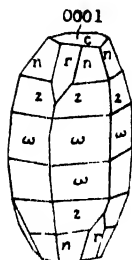


FIG. 23. Corundum.
(After Dana.)
n (2243), z (2241), r (1011)
(14. 14 28. 3)

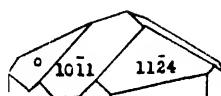


FIG. 24. Tourmaline
(After Dana.)
o (1124), r (1011), m (1010), a (1120), c (0112).

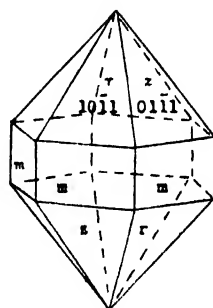


FIG. 25. Rhombohedra (r), (z), and Prism (m).
e.g. Quartz

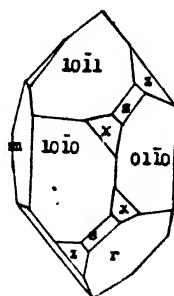


FIG. 26. Quartz, right-handed
(After Dana.)
r (1011), z (0111), s (1121),
x (5161), m (1010).

ORTHORHOMBIC SYSTEM

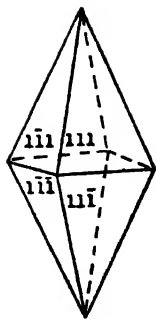


FIG. 27.
Pyramid (p).

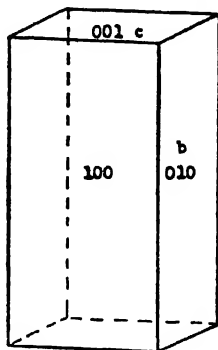


FIG. 28. Macropinacoid (100), Brachypinacoid (010) and Basal Pinacoid (001).

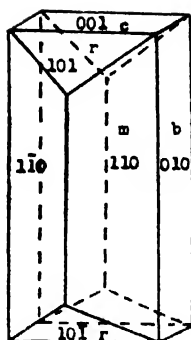


FIG. 29. Prism (m), Pinacoids (b), (c), and Macrodome (r).
c.g. Staurolite.

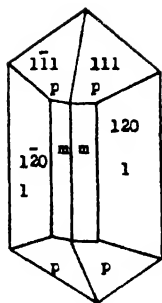


FIG. 30. Prisms (m) and (b) and Pyramids (p).
c.g. Topaz.
(After Dana.)

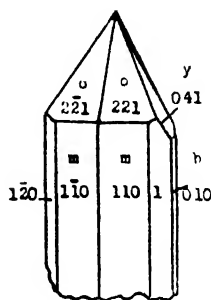


FIG. 31. Prisms (m) and (l) Pyramid (o), Brachydome (y).
c.g. Topaz.
(After Dana.)

MONOCLINIC SYSTEM

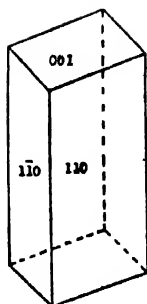


FIG. 32.
Prism (m) and
Basal Pinacoid
(c).



$\frac{001}{100}$



$\frac{001}{101}$
 $\frac{100}{\bar{2}01}$
 $\frac{101}{\bar{1}01}$



110



FIG. 34. *Epidote*.
(After Dana.)

FIG. 33. Orthopinacoid
(a), Pyramid (n), Basal
Pinacoid (c), Orthodome
(r).
e.g. Epidote.

TRICLINIC SYSTEM

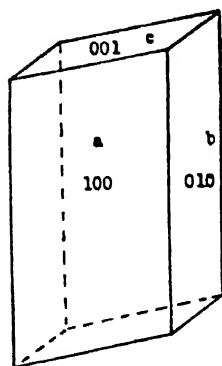


FIG. 35. Basal-
(c). Macro- (a) and
Brachy-pinacoids
(b).

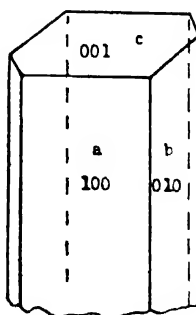


FIG. 36. As Fig. 36.
e.g. Kyanite.

ACTINOLITE

(AMPHIBOLE GROUP)

[Pl. 1A, between pp. 32-33]

Chem. Comp. $2\text{CaO} \cdot 5(\text{Mg}, \text{Fe})\text{O} \cdot 8\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Slender prisms, often euhedral.

Structure. Crystalline; individual crystals or fibrous aggregates.

Cleavage. Perfect $\parallel (110)$, sometimes observed $\parallel (100)$.

Fracture. Irregular.

Hardness. 5.

Spec. Grav. 3.0-3.3.

Lustre. Vitreous.

Colour. Bright green to grey-green; yellow. Transparent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.614$, $\beta = 1.630$, $\gamma = 1.641$. Birefringence strong, $\gamma - \alpha = 0.027$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. $Bxo = Z$ inclined at low angle to c axis; maximum extinction angle $Z \wedge c$ varies from 8° to 20° ; normally 16° . $2V = 80^\circ$. Prismatic grains show \parallel length. $Y \parallel b$. Pleochroism moderate to weak: $X =$ pale yellow, $Y =$ yellow-green, $Z =$ pale to dark green. Maximum absorption when vibrations are \parallel trace of Z . Dispersion, $\rho < \nu$ weak.

Characters in Sediments. Usually as distinctive yellowish-green, fibrous aggregates or single grains, some individuals being weakly pleochroic, others showing no reaction in this respect. The detrital varieties usually have a low extinction angle; they frequently show alteration to chloritic matter and contain iron-ore and carbonaceous inclusions.

Occurrence. New Red Sandstone of the West of England¹; Upper Lias—Lower Inferior Oolite sands of the West of England²; Greensand Bed at the Base of the Thanet Sand³; Thanet Sands and Reading Beds of the London Basin⁴; Miocene Sands of Los Angeles Basin, S. California, and other foreign examples rich in amphibole minerals⁵; from the Box-Stones occurring below and within the Pliocene Coralline and Red Craggs of Essex and Suffolk⁶; later Tertiary deposits of the East of England⁷; alluvium of R. Tigris⁸; the Loess⁹; in the Beach Sands of Cedar Point, Ohio⁹; in association with dolomite in the sands at Fulford, East Yorkshire¹⁰; in sands of the Kettleman Hills, California, U.S.A.¹¹

Possible Sources of Derivation. Crystalline schists; granular or massive metamorphic rocks; secondary alteration product of ferromagnesian silicates in igneous rocks.

REMARKS.—Not a common mineral in detrital sediments unless *all* types of fibrous hornblende are designated as actinolite. *Nephrite*, the pale to dark green fibrous variety of actinolite or tremolite (p. 197), is often known as *jade*.

AEGIRINE

(PYROXENE GROUP)

[Pl. 1B, between pp. 32-33]

Chem. Comp. $\text{NaFeSi}_2\text{O}_6$ (A. N. Winchell).*System.* Monoclinic.*Habit.* Elongated prismatic crystals often with vertical striations and obtuse terminations. Twinning common on (100).*Structure.* Crystalline.*Cleavage.* Perfect \parallel (110). Parting noted on (010) or (001).*Fracture.* Irregular.*Hardness.* 6-6.5.*Spec. Grav.* 3.5-3.55.*Lustre.* Vitreous to resinous.*Colour.* Leaf green, dark green to greenish black. Transparent to opaque.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Poor conductor.*Opt. Prop.* R.I. high, $\alpha = 1.742$, $\beta = 1.768$, $\gamma = 1.787$. Birefringence strong, $\gamma - \alpha = 0.045$. Optically biaxial, negative. Optic axial plane \parallel (010). $Bxa \div (X)$ makes small angle (2° - 5°) with c in the obtuse angle β . $Y \div b$. $2V = 81^\circ$. Usually pleochroic: $X =$ olive green $\searrow Y =$ lighter shade $\searrow Z =$ yellow green. Dispersion $\rho \searrow v$, inclined.*Characters in Sediments.* Aegirine is rare in sediments, owing to its relatively unstable character and is recorded principally from recent deposits, where it normally assumes yellow or olive green, prismatic features ('narrow green grains') with distinctive pleochroism. Careful measurement of its optical properties, notably the small extinction angle, negative sign and elongation, coupled with its characteristic colour and pleochroism, serve to distinguish it from hornblende or ordinary augite, two minerals with which it is at first glance liable to be confused.*Occurrence.* In the Lower Cambrian, Massif de Ste. Croix, Central Poland¹; in the Triassic iron-ores of Poland²; in the Lower Miocene of the San Onofre Breccia, California³; in the Chinese Loess⁴; in the dune sands of South Wales⁵; in Shore sand, S. Coast, Greenland⁶.

AGATE

See Chalcedony, p. 73.

ALBITE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$.

System. Triclinic.

Habit. Tabular, prismatic; commonly twinned on Albite law (010), Pericline law (about b axis); less commonly on Carlsbad law (about c axis), Baveno law (021) or Manebach law (001).

Structure. Crystalline.

Cleavage. Perfect \parallel (010) almost invariable; also \parallel (001). Less common \parallel (110). Parting \parallel (100).

Fracture. Conchoidal, irregular.

Hardness. 6.

Spec. Grav. 2.61.

Lustre. Vitreous, pearly.

Colour. Colourless, grey.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.525$, $\beta = 1.529$, $\gamma = 1.536$. Birefringence moderate, $\gamma - \alpha = 0.011$. Optically biaxial, positive. Optic axial plane nearly \perp (010). $Bxa = Z$. Oblique extinction: $\perp X + 77^\circ$; $\perp Z + 21^\circ$; $\parallel (001) + 3^\circ$; $\parallel (010) + 20^\circ$. $2V = 74^\circ$. $2E = 134^\circ$. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Albite grains in sediments are almost always diagnosed by the presence of twin lamellae, coupled with a R.I. practically the same as Canada balsam (sometimes slightly lower) and a superficial decomposition to muscovite and kaolinite. Otherwise distinction between them and other feldspars is in most cases impossible with single grains unless the crystal face presented can be determined and precise optical measurements made thereon. Inclusions are common, e.g. quartz, iron ores, zircon; also gaseous and liquid.

Occurrence. In the Ordovician Grit of Anglesey¹; in the Alpine Trias near Modane²; in the Upper Kimmeridge Clay—Portland Sand of

Buckinghamshire etc.³; in the Jurassic, Cretaceous and Eocene limestones of the Swiss Alps⁴; in the Turonian Stage, Argentine⁵; in the Flysch (Upper Cretaceous) limestone of the Pyrenees⁶; in the later Tertiary deposits of East England⁷; in the Dartmoor detritals⁸.

Later Records. In the Denbigh Grits and Wenlock Greywackes, N. Wales (chessboard type)⁹; in the Yoredale limestone¹⁰.

Possible Sources of Derivation. Igneous Rocks.

REMARKS.—Regular intergrowths of albite and orthoclase (p. 31) or microcline (p. 143) are known as *perthite* or *micropertthite*.

References

- ¹ E. Greenly and P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **88**, 1932, p. 297.
- ² G. Rose, *Pogg. Annalen Phys. Chem.*, **125**, 1865, p. 457.
- ³ E. Neaverson, *Proc. Geol. Assoc.*, **35**, 1924, p. 336.
- ⁴ F. J. Kaufmann, *Beitr. Geol. Karte Schweiz*, **24**, 1886, p. 581.
- ⁵ L. Déverin, *Actes Soc. Helv. Sci. Nat.*, 1925, p. 138.
- ⁶ J. de Lapparent, *C.R. Acad. Sci., Paris*, **167**, 1918, p. 999.
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 336.
- ⁸ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 46.
- ⁹ W. A. Cummins, *Geol. Mag.*, **94**, 1957, p. 440.
- ¹⁰ W. W. Black, *Geol. Mag.*, **86**, 1949, p. 129.

General Reference

- H. L. Alling, The Mineralogy of the Feldspars, *Journ. Geol.*, **31**, 1923, p. 282, 353.

ALLANITE (ORTHITE)

(EPIDOTE GROUP)

Chem. Comp. $4(\text{Ca}, \text{Fe})\text{O}, 3(\text{Al}, \text{Ce}, \text{Fe}, \text{Di})_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Tabular $\parallel (100)$, elongated $\parallel b$.

Structure. Crystalline, massive.

Cleavage. Poor $\parallel (001)$, (100) , (110) .

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 4.15 (decreases with alteration).

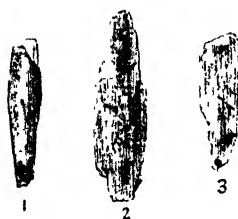
Lustre. Vitreous, dull.

Colour. Brown, black.

Mag. Prop. ?

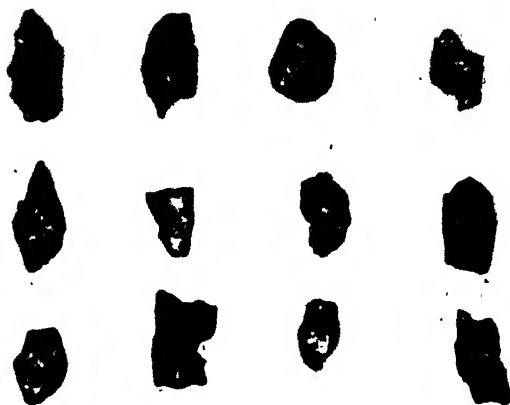
Elect. Prop. ?

Opt. Prop. Highly variable. R.I. high, $\alpha \approx 1.727$, $\beta = 1.739$, $\gamma = 1.751$. Birefringence moderate, $\gamma - \alpha = 0.024$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. $Bxa = X \wedge c = 30^\circ\text{--}40^\circ$. Or optic axial plane $\perp (010)$, $X \wedge c = 22^\circ\text{--}41^\circ$. $Y = b$. $2V = \text{large}$. Pleochroism: $X = \text{yellow or brown}$, $Y = \text{dark brown}$, $Z = \text{dark red brown}$. Dispersion strong, $\rho > \nu$. Optically positive crystals also known, with variable R.I. ($\beta = 1.65\text{--}1.78 \pm$) and pleochroism $X = \text{colourless}$, $Z = \text{pale green}$. Isotropic (altered) forms also known, of lower S.G. (3.4) and R.I. $n = 1.61 \pm$.



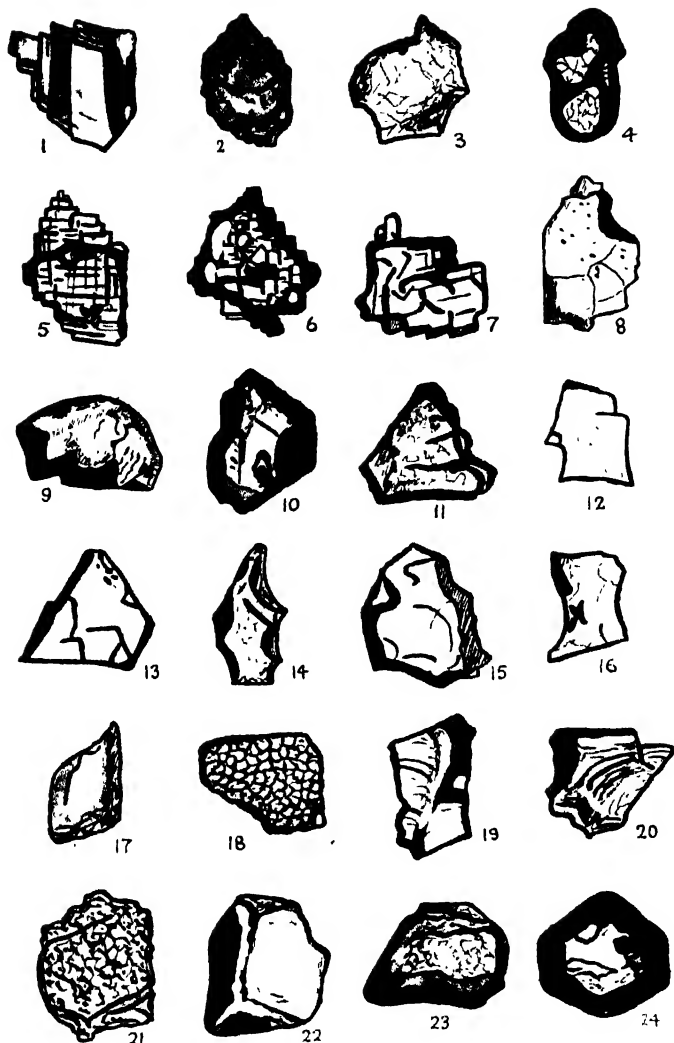
A. ACTINOLITE.

- 1, 2 Recent Sand, River Tigris, Iraq. [x 40]
 3 Shore Sand, Kynance, Cornwall. [x 4]



B. AEGIRINE.

Zircon Sand Vigo, Spain. [x 40.]



ALMANDINE GARNET FROM DIFFERENT BRITISH STRATIGRAPHICAL HORIZONS.

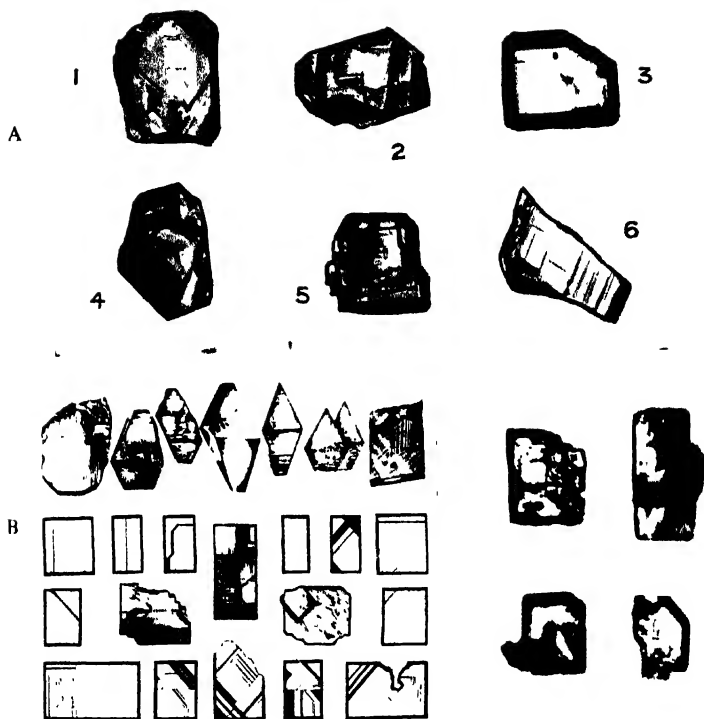
- | | |
|---|---|
| 1 Torridonian (after Bosworth) | 14 Corallian, Abbotsbury, Dorset |
| 2 Quartzite (Cambrian), Malvern | 15 Portland Sand, Portsmouth, Dorset |
| 3 Hollybush Sandstone (Cambrian), Malvern | 16 Ashdown Sand (Wealdon), Hastings, Sussex |
| 4 May Hill Sandstone (Silurian), Malvern | 17 Upper Greensand, Ielsworth, Oxon |
| 5, 6, 7. Millstone Grit, Northumberland | 18 Thanet Sand, Plumstead, Kent |
| 8 Fuelay, Coal Measures, Ferguslie, Paisley, N.B. | 19 Woolwich and Reading Sand, St. Albans |
| 9 Permian, Lynemouth, Northumberland | 20 Blackheath Beds, Elmstead, Surrey |
| 10, 11 Bunter, Hoylake, Cheshire | 21 Bagshot Sands, Bournemouth |
| 12 Lias, Napton, Rugby | 22 Phocene, Bentley, Suffolk |
| 13 Northampton Sands, Northampton | 23 Glacial Sand, Kimpton, Herts |
| | 24 Shore Sand, Speeton, Yorks. [All x 5] |



AMBLR.

Littoral Deposits, Baltic Coast, East Prussia. [Nat. Size]

PLATE 3



A, B, C. ANATASE.

A 1, 2, 3, 6 Pliocene Sands, St. Keverne, Cornwall [1, 3, x 120, 2, 6, x 70.]
 A 4, 5 Tunbridge Wells Sand, Tunbridge Wells, Kent [x 70.]

B Typical Crystals and Fragments of Dartmoor Anatase (from brush-drawings
 by A. Brannmall) Grade-size, 0.2-1.4 mm
 Top Row Octahedrite Unit pyramid, etc
 Remainder Tabular, bas. 1 plane and (111), showing geometric patterning.

C Middle Jurassic, Yorkshire (Authigenic), [x 105.]

Characters in Sediments. Irregular grains, similar to epidote in detrital form, but liable to show considerable variation in appearance due to alteration products. Colour and other physical properties may vary greatly in the same grains. May be intimately associated with epidote. The optical variations are such that great care is necessary in diagnosis, which is not always directly possible by microscopical means alone.

Occurrence. In borehole samples, Viareggio, Italy¹; in borehole samples from the Plain of Lombardy²; in the black sands of Idaho³; in submarine deposits of the Arctic Ocean⁴.

Possible Sources of Derivation. Acid igneous rocks. Metamorphic rocks. Certain iron ores.

REMARKS.—Allanite is not a common species and its occurrence in sediments will be localized in environments which are favourably placed as regards appropriate source of origin of detritus.

References

¹ I. Chelussi, *Boll. Soc. Geol. ital.*, **43**, 1924, p. 17.

² *ibid.*, p. 161.

³ E. V. Shannon, *Proc. U.S. National Mus.*, **60**, 1921, p. 1.

⁴ J. Thoulet, *C.R. Acad. Sci., Paris*, **148**, 1909, p. 884.

ALLOPHANE*

Chem. Comp. Al_2O_3 , SiO_2 , $n\text{H}_2\text{O}$.

System. Isometric or amorphous.

Habit. White amorphous powder. Often colloidal.

Structure. Massive, encrustations.

Cleavage. None.

Fracture. None.

Hardness. 3.

Spec. Grav. 1.86.

Lustre. Earthy.

Colour. Blue, green, white.

Mag. Prop. ?

Elect. Prop. ?

Opt. Prop. R.I. low, $n = 1.49$. Optically isotropic.

Characters in Sediments. Identified in encrusting masses in certain clay deposits and characterized by its colour, softness, low S.G. and R.I.

Occurrence. In the clays of Maryland, U.S.A.¹

Possible Sources of Derivation. Ball clay, china clay, shale, Fuller's earth, coal.

Reference

¹ H. Ries, *Maryland Geol. Surv.*, **4**, 1902, p. 215.

C. S. Ross and P. F. Kerr, The Clay Minerals and their Identity, *Journ. Sed. Pet.*, 1, 1931, p. 55.

G. W. Brindley and ors., X-ray Identification and Crystal Structures of Clay Minerals (*Miner. Soc., London*), 1951, p. 48.

ALMANDITE (GARNET GROUP)

[Pl. 2, between pp. 32-33]

Chem. Comp. $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$.

System. Isometric.

Habit. Dodecahedron (110), trapezohedron (211) or combination of both forms. No twinning.

Structure. Crystalline, massive.

Cleavage. Usually none; poor || (110).

Fracture. Irregular, subconchoidal.

Hardness. 7.

Spec. Grav. 4.1-4.3.

Lustre. Vitreous, resinous.

Colour. Red.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. very high, $n \approx 1.766-1.830$. Optically isotropic, though some examples rarely yield anomalous interference tints due to strain.

Characters in Sediments. Detrital almandite is commonly irregular, often fractured, sometimes well rounded; generally devoid of recognizable crystal faces. Platy grains determined by a poor (110) cleavage, showing subconchoidal fracture and prominent re-entrant angles sometimes met with. Inclusions common, e.g. quartz, iron ore; in the Dartmoor detritals A. Brammall has recorded quartz, feldspar, apatite, zircon, biotite, rutile, iron ore. Note particularly surface characteristics: many detrital almandite grains provide distinctive features, e.g. pitting, grooving, spotting, rectangular patterning, deep colour staining and sometimes 'etched' appearance.

Occurrence. Almandite is the most widespread and persistent variety of garnet in detrital sediments and in the British Isles is found in the oldest to the youngest rocks with few exceptions. Among the best horizons for this variety are: Old Red Sandstone, Herefordshire; Calcareous Sandstone, Midlothian region, Scotland; Millstone Grit, Northumberland, Durham and Yorkshire; Permian rocks, South Devonshire; Upper Keuper, Leicestershire; Estuarine Sandstones, Yorkshire and Northamptonshire; various Glacial Sands and Gravels of East Anglia, Plateau Gravels of the London Basin and shore sands of West Cornwall (Marazion, St. Ives). (N.B.—The comparative scarcity of garnet in the Tertiary deposits of Cornwall is noteworthy: see general reference* below.)

Later Records. In Downtonian, Tenbury, Worcestershire¹; in Cementstone Group, Lower Carboniferous, Northumberland²; in Lower

Greensand, East Kent³; in Lower Greensand, Western Weald⁴; in Reading Beds, Reading⁵; in Beach Sand, Carbis Bay, Cornwall⁶.
Possible Sources of Derivation. Igneous and metamorphic rocks, particularly crystalline gneisses and schists. Alluvial deposits.

REMARKS.—Almandite varies widely in detrital sediments, specific physical features often typifying grains from definite horizons; on this account it is of great importance for correlation purposes and also for suggesting the conditions under which deposition took place. In recent years, much has been written on corrosion and stability of garnet (see *General References* below, marked†).

References

- ¹ P. S. Walder, *Proc. Geol. Assoc.*, **52**, 1941, p. 247.
- ² D. A. Robson, *Quart. Journ. Geol. Soc.*, **112**, 1956, p. 254.
- ³ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- ⁴ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
- ⁵ P. S. Walder, *Proc. Geol. Assoc.*, **51**, 1940, p. 215.
- ⁶ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 78.

General References

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 *P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 221.
 A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 321 and Fig. 27.
 C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 389 and Pl. 16 (for alluvial occurrences).
 A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 35.
 L. Hawkes and J. A. Smythe, Garnet-bearing Sands of the Northumberland Coast, *Geol. Mag.*, **68**, 1931, p. 345.
 †F. J. Pettijohn, *Journ. Geol.*, **49**, 1941, p. 610.
 †F. Smithson, *Geol. Mag.*, **78**, 1941, p. 97.
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 †V. T. Allen, *Journ. Sed. Pet.*, **18**, 1948, p. 38.

AMBER

[Pl. 3, between pp. 32–33]

Chem. Comp. Hydrocarbon, resin.

System. Amorphous.

Habit. Subangular 'pebbles'; irregularly shaped; nodular.

Structure. Indefinite.

Cleavage. None.

Fracture. Conchoidal; uneven, thus commonly found.

Hardness. 2–2.5.

Spec. Grav. 1.07.

Lustre. Resinous, waxy or vitreous.

Colour. Brown, orange, pale yellow.

Mag. Prop. Non-magnetic.

Elect. Prop. Good conductor. Develops negative charge when rubbed and will attract small pieces of paper, bran, etc.

Opt. Prop. Inert. R.I. low, $n = 1.535$ (approx.).

Characters in Sediments. In alluvial and coastal deposits, as subangular, scratched and worn pellets and particles, probably never far distant from source.

Occurrence. In London Clay, Eocene, Highgate, London ('*Highgate Resin*' or *Copalite*)¹; in coastal deposits along sea-board of East Anglia (Norfolk, Essex)²; abundant on Baltic coast between Dantzic to Memel, especially from Pillau to Dorf Gross-Hubnicken³.

Possible Sources of Derivation. Derived from various trees, coniferous chiefly, e.g. pinus.

REMARKS.—Amber (= Succinite) is fossil resin of organic origin. It frequently contains insect 'inclusions'. Some varieties are fluorescent in ultra-violet light (Sicily). There is considerable variation in composition of amber, as would be expected from its nature and diverse provenances.

References

¹ H. H. Read, *Rutley's Elements of Mineralogy*, 24th ed. (Murby, London), 1949, p. 330.

² Author's observations (see also ref. 3 below).

³ J. D. Dana, *System of Mineralogy*, 6th ed. (Kegan Paul, Trench, Trübner, London), 1892, p. 1003.

General Reference

C. E. N. Bromhead, *Proc. Geol. Assoc.*, **59**, 1948, p. 71.

ANALCITE

(ZEOLITE GROUP)

Chem. Comp. $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Isometric. ?Pseudoisometric.

Habit. Trapezohedral; complex penetration, twins.

Structure. Crystalline, massive.

Cleavage. Difficult cubic cleavage.

Fracture. Irregular.

Hardness. 5-5.5.

Spec. Grav. 2.2-2.29.

Lustre. Pearly.

Colour. White, grey, greenish white.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $n = 1.487$. Isotropic but sometimes optically anomalous. Some crystals are uniaxial, R.I. low, $\epsilon = 1.486$, $\omega = 1.487$; negative sign. Biaxial crystals also known having very small optic axial angle and weak birefringence, $\gamma - \alpha = 0.001$; such crystals have negative sign.

Characters in Sediments. Detrital analcite is a rare and local constituent of sediments, chiefly of recent date. It occurs in angular to sub-angular, polygonal grains, difficult of identification without close optical tests. Its low R.I., lack of colour and isotropism serve to suggest a member of the zeolite group, but confusion with certain forms of leucite and sodalite (in small grains) may be easy unless

chemical tests are applied. It readily gelatinizes with HCl and gives strong sodium reaction to flame test.

Occurrence. Middle Cretaceous clays of Duinzen¹; Eocene Lake-beds deposits of Utah and Colorado, U.S.A.²; Quaternary Lake Beds of playa deposits of Arizona, U.S.A.³; deep sea deposits⁴.

Possible Sources of Derivation. From igneous rocks, particularly basic hypabyssal and volcanic types and amygdaloidal forms of the latter (cavities filled with zeolites): *e.g.* analcite dolerite and analcite basalt.

References

¹ K. von Seebach, *Georg. Augustus Univ., K. Gesellsch. Wiss. Göttingen. Nachr.*, 1862, p. 334.

² W. H. Bradley, *U.S. Geol. Surv., Prof. Paper* 158-A, 1929.

³ C. S. Ross, *Amer. Min.*, 13, 1928, p. 195.

⁴ H.M.S. Challenger, Report on Scientific Results of the Voyage (Admiralty) 1891.

ANATASE

(OCTAHEDRITE)

[Pl. 4, between pp. 32–33]

Chem. Comp. TiO_2 .

System. Tetragonal.

Habit. Octahedral, acute or obtuse; often tabular.

Structure. Crystalline, rarely massive.

Cleavage. Perfect \parallel (001) and (111).

Fracture. Subconchoidal, uneven.

Hardness. 5.5–6.

Spec. Grav. 3.82–3.95.

Lustre. Adamantine, submetallic.

Colour. Yellow, brown, indigo-blue, black. Transparent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderately good conductor.

Opt. Prop. R.I. very high, $\omega = 2.554$, $\epsilon = 2.493$. Birefringence strong, $\omega - \epsilon = 0.061$. Optically uniaxial, negative. Non-pleochroic except in thick grains: ω = pale blue or yellow, ϵ = dark blue or orange. Basal sections isotropic. Occasionally in the darker coloured varieties a biaxial figure with small optic axial angle is observed.

Characters in Sediments. Tabular (basal) grains are most common (001), often bevelled by (111) faces. Such grains exhibit interference figure. Parallel intergrowth of tabular varieties common. Pyramidal forms, simple or compound, also observed; these may show striations \parallel intersection with prism (110). Less common are the angular cleavage flakes or irregularly fractured grains. Two distinct coloured varieties are met with, the yellow or yellow-brown and the indigo-blue or greenish-blue types. Dark coloured grains are almost metallic and opaque. Inclusions of quartz, tourmaline, zircon, rutile, cassiterite, iron-ores have been noted. Zoning or 'geometric patterning' frequent in some developments: see under 'Remarks' below. Both primary and secondary grains occur, sometimes in the same deposit; the

latter are probably derived *in situ* from the decomposition of titaniferous minerals such as ilmenite and usually show marked euhedrism. The former are detrital, evinced by a certain degree of wear (rounding) consequent on prolonged abrasion.

Occurrence. In Ordovician sediments¹; in Devonian grits, slates etc. of the Torquay district, Devonshire²; in the Old Red Sandstone of the West Midlands³; in the Permo-Triassic rocks of the Midlands⁴; in the Bunter Pebble Bed of the West of England⁵; in the New Red Sandstone of the West of England⁶; in the Upper Lias—Lower Inferior Oolite sands of the West of England⁷; in the Kellaways Rock (Oxfordian) of the Peterborough District⁸; in the Wealden Sands (Lower Cretaceous) of Tunbridge Wells and other areas in the Weald⁹; in Cretaceous sands of the Haldon Hills, etc., West of England¹⁰; in the Bagshot Beds (Eocene) of Essex¹¹; in the Pliocene sands, St. Keverne, Cornwall¹²; in later Tertiary deposits of Eastern England¹³; in alluvial sands, Dartmoor, Devonshire^{14,15}; in certain surface deposits of S.E. Devonshire¹⁶.

Later Records. In Middle Jurassic deposits, Yorkshire¹⁷; in Lower Greensand, East Kent¹⁸; in Lower Greensand, Western Weald¹⁹; in mineral matter, Trinidad Lake Asphalt, Trinidad, B.W.I.²⁰.

Possible Sources of Derivation. Crystalline igneous and metamorphic rocks; when abundant probably authigenic, derived *in situ* from decomposition of ilmenite or other titaniferous species: see reference¹⁴.

REMARKS.—The mineralogy and geochemistry of anatase have been very fully discussed by A. Brammall and H. F. Harwood in connexion with its occurrence at Dartmoor, while in a later contribution the former author figures and describes some beautiful examples of both zoned tabular and pyramidal types found in Dartmoor detrital deposits; both these papers should be consulted for this interesting mineral (see references^{14,16}).

References

- ¹ P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, **14**, 1924, p. 14.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 137.
- ³ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 513.
- ⁴ W. F. Fleet, *Proc. Geol. Assoc.*, **38**, 1927, p. 1.
- ⁵ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 622 and Pl. 32.
- ⁶ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 231.
- ⁷ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 254.
- ⁸ E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 23.
- ⁹ H. B. Milner, *Proc. Geol. Assoc.*, **34**, 1923, Pl. 5 and p. 290; also **36**, 1925, p. 315.
- ¹⁰ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 209, 218.
- ¹¹ S. W. Wooldridge, *Proc. Geol. Assoc.*, **35**, 1924, p. 377.
- ¹² H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 363.
- ¹³ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 338.
- ¹⁴ A. Brammall and H. F. Harwood, *Mineral Mag.*, **20**, 1923, p. 20.
- ¹⁵ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 30.
- ¹⁶ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 147.
- ¹⁷ F. Smithson, *Geol. Mag.*, **91**, 1954, p. 180.

¹⁸ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.

¹⁹ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

²⁰ Author's observations.

General Reference

J. A. Butterfield, An Occurrence of Anatase in the Millstone Grit of Yorkshire, *Trans. Leeds Geol. Assoc.*, **5**, 1934-5, p. 142.

ANAXITE*

(See KAOLINITE, p. 130)

ANDALUSITE

[Pl. 5A, between pp. 48-49]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Fe and Mn may be present.

System. Orthorhombic.

Habit. Prismatic, rarely euhedral, square prisms, acicular or fibrous.

Structure. Usually crystalline.

Cleavage. Perfect $\parallel (110)$, imperfect $\parallel (100)$, more rarely $\parallel (010)$.

Fracture. Uneven and irregular.

Hardness. 7.5.

Spec. Grav. 3.1-3.2.

Lustre. Vitreous.

Colour. Colourless, white and pale shades of red, green, brown and violet. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.634$, $\beta = 1.639$, $\gamma = 1.643$. Birefringence weak, $\gamma - \alpha = 0.009$. Optically biaxial, negative. $2V = 85^\circ$. Length fast. Optic axial plane $\parallel (010)$. $Bxa \perp (001)$. $Bxa = X \parallel c$; $Y \parallel b$, $Z \parallel a$. Straight extinction \parallel prism-edge. Pleochroism intense in some varieties; $X \succ Y$ or Z ; Y and Z colourless, X rose or blood-red. Dispersion weak, $\rho \succ \nu$.

Characters in Sediments. Colourless, 'glassy'; sometimes with pinkish tinge; grains very variable in form; commonly irregular and sub-angular, but prismatic types also met with. Frequently shows presence of inclusions of graphite or carbonaceous matter,† also alteration products such as sericite or kaolinite, all causing a turbid appearance of the mineral. These features and its negative sign serve to differentiate andalusite from topaz (with which it may sometimes be confused), but the pink to blood-red pleochroism of the former, when present, is an infallible guide.

Occurrence. In Millstone Grit of Yorkshire¹; in Cretaceous and Eocene sands of the Oxford district²; in the Cretaceous and Tertiary deposits of the West of England³; in the Pliocene deposits of St. Keverne, Cornwall⁴; in the sands of Pliocene age at St. Agnes Beacon, New-quay⁵; in the later Tertiary deposits of the East of England⁶; in the

* See Ch. III, p. 308.

† Chialstolite; see p. 77.

Pliocene deposits of Sanderstead, Surrey⁷; in the ferruginous sands of Netley Heath, Surrey⁸; in the Pliocene deposits of Cornwall and Lenham, Kent⁹; in the Dartmoor detritals¹⁰; in the surface deposits of S.E. Devonshire¹¹; in the shore sand of St. Ives Bay, Cornwall¹². *Later Records.* In Lower Greensand, East Kent¹⁴; in Beach Sand, Carbis Bay, Cornwall¹⁵; in mineral matter, Trinidad Lake Asphalt, Trinidad, B.W.I.¹⁶.

Possible Sources of Derivation. Granites and contact metamorphic rocks.

REMARKS.—At one time detrital andalusite was thought to be restricted in the British Isles to Tertiary deposits, but as the occurrences above show, it ranges back at least as far as Palæozoic. It certainly gets extremely rare with increasing geological age of sedimentary rocks but may be looked for almost universally in Pliocene deposits, according to the author's observations. See also references to chialstolite occurrences on p. 77, paragraph on p. 440, and reference ¹³ below.

The manganese-bearing variety, manganandalusite or viridine, is characterized by its dark green colour, yellow-green pleochroism and high R.I., $\alpha \approx 1.662$, $\beta \approx 1.671$, $\gamma \approx 1.691$ (*A. N. Winchell*). This variety has not so far been recorded from sediments.

References

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- ² G. M. Davies, *Mineral. Mag.*, **17**, 1915, p. 218.
- ³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 205.
- ⁴ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 363.
- ⁵ J. S. Flett, *Mem. Geol. Surv.*, Great Britain Sheet 346, 1906, p. 63.
- ⁶ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 339.
- ⁷ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, **37**, 1926, p. 92.
- ⁸ P. G. H. Boswell, in H. G. Dines and F. H. Edmunds, *Geology of the Country around Aldershot and Guildford*, *Mem. Geol. Surv.*, Great Britain, 1929, p. 114.
- ⁹ H. H. Thomas, *Mineral. Mag.*, **15**, 1909, p. 241.
- ¹⁰ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 27.
- ¹¹ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 145.
- ¹² T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 120.
- ¹³ P. G. H. Boswell, *The Rarer Minerals of British Sedimentary Rocks*, *Trans. Geol. Soc. Glasgow*, **18**, 1926–27, p. 133.
- ¹⁴ G. A. Worrall, *Proc. Geol. Surv.*, **65**, 1954, p. 193.
- ¹⁵ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.
- ¹⁶ Author's observations.

ANDESINE

(PLAGIOCLASE-FELSPAR GROUP)

[Pl. 5B, C, between pp. 48–49]

Chem. Comp. Ab_3An_2 . ($\text{Ab} = \text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$.
 $\text{An} = \text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$).

System. Triclinic.

Habit. Tabular, prismatic. Polysynthetic twinning on (010) almost invariable (Albite law); also Pericline law (about b axis); Carlsbad law (about c axis); Baveno law (021); Manebach (001).

Structure. Crystalline; massive.

Cleavage. Perfect \parallel (001) and (010); indifferent \parallel (110). Parting \parallel (100).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 2.68.

Lustre. Pearly.

Colour. Colourless.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.550$, $\beta = 1.553$, $\gamma = 1.557$. Birefringence weak, $\gamma - \alpha = 0.007$. Optically biaxial positive. Oblique extinction: $X' \wedge (010) = \text{max. } 25^\circ$; on 010 $X' \wedge (001) = 8^\circ$; on 001 $X' \wedge (010) = 2^\circ$. Optical properties variable with composition. $2V = 88^\circ$. Dispersion about bxa , $\rho > \nu$.

Characters in Sediments. Detrital andesine is probably more common in sediments than records seem to indicate. Grains may be expected to be of irregular shape, clear, colourless and with characteristic twinning. Accurate diagnosis depends on being able to determine the crystallographic orientation of the grain under observation, otherwise distinction from oligoclase or albite may not be possible. The R.I. may afford a clue, being *lower* than Canada balsam for these minerals and *higher* for andesine. Decomposition products include sericitic mica, kaolinite and complex hydrous aluminium silicates. Inclusions common, quartz, iron ores, zircon, gaseous or liquid. Occasional zoning.

Occurrence. In the Old Red Sandstone of the Cardiff district¹; in the soils of Java^{2,3}; in sands at Kettleman Hills, California, U.S.A.⁴.

Possible Sources of Derivation. Igneous rocks, particularly intermediate hypabyssal and volcanic types.

References

- ¹ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 499.
- ² G. A. Neeb, *Overdruk uit de Handelingen v/h 7^{de} Ned. Ind. Natuurwetenschappelijk Congres*, 1936, p. 695.
- ³ D. A. Carroll, *Journ. Roy. Soc., West. Australia*, **20**, 1933-4, p. 100.
- ⁴ N. M. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, **18**, 1934, p. 1562.

ANDRADITE

(GARNET GROUP)

Chem. Comp. $3(\text{Ca, Mg, Fe})\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 3\text{SiO}_2$.

System. Isometric.

Habit. Dodecahedral (110), trapezohedral (211) or combination of both. Twinning unknown.

Structure. Crystalline.

Cleavage. None.

Fracture. Irregular.

Hardness. 7.

Spec. Grav. 3.78.

Lustre. Vitreous.

Colour. Variable, yellow, brown, green, black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. very high, $n = 1.865$. Isotropic, but sometimes optically anomalous: biaxial with high interference tints.

Characters in Sediments. A rare constituent of sediments, characterized by yellow to green colour, very high R.I. and tendency to dodecahedral habit. Incipient alteration to epidote, calcite or feldspar characteristic; in the more ferriferous type, to limonite. Zoning observed in some examples.

Occurrence. In the Silurian Rocks of Scotland¹.

Possible Sources of Derivation. Contact metamorphosed limestone; schist; syenites.

REMARKS.—See also *melanite*, the black variety of andradite (p. 142).

Reference

¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (*Glasgow*), 1929, p. 556.

ANHYDRITE

[Pl. 6, between pp. 48–49]

Chem. Comp. CaSO_4 .

System. Orthorhombic.

Habit. Prismatic, tabular, fibrous (radial, spherulitic), granular and as rectangular cleavage flakes. Also twinned about (012) and lamellar (101).

Structure. Crystalline, massive; curvilinear.

Cleavage. Three pinacoidal directions: very perfect \parallel (001) and (010); less perfect \parallel (100); the three when developed give rise to square-shaped flakes.

Fracture. Irregular, splintery.

Hardness. 3–3.5.

Spec. Grav. 2.899–2.985. (Note difference from Gypsum, p. 118).

Lustre. Pearly on (001) flakes; vitreous on (010) and (100) flakes. Sometimes resinous.

Colour. Colourless, white, grey, pink or bluish-white. Colourless in thin grains or sections.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. variable, $\alpha = 1.570$, $\beta = 1.575$, $\gamma = 1.614$. Birefringence strong, $\gamma - \alpha = 0.044$. Biaxial positive. $2V = 42^\circ$. Optic axial plane \parallel (010). $Bxa \perp$ (100). $Bxa = Z$. $X \parallel c$, $Y \parallel b$, $Z \parallel a$. Straight extinction. Non-pleochroic. Dispersion $\rho < \nu$.

Characters in Sediments. Extremely variable in form, some of the principal varieties being shown in Pl. 6. An interesting, but little known species as free crystalline grains. Diagnosed chiefly by its S.G., R.I. (a certain amount of 'twinkling' is observed in many examples), cleavages and positive optical character. Liable to confusion with barite, sometimes kyanite, topaz, sillimanite, possibly enstatite.

Distinguish by careful S.G. and optical tests, also (if necessary) with HCl which causes no effervescence on solution, thus differentiating it from all carbonates. Well cleaved, rectangular grains exhibit remarkable cubic appearance and are unique in development. Note that (001) cleavage flakes will yield a biaxial figure (emergence of *bxo*) which is 'central', in contrast with figure yielded by calcite (eccentric or partial). Aggregates and compound grains also observed. Inclusions of iron-ores common; zoning developed in occasional types; see *Pl.* 6, nos. 11–14. In appropriate circumstances anhydrite grains exhibit every stage in alteration to gypsum, the most notable features being loss of crystal form and relief (decreased R.I.), change of optical properties and sometimes the formation of definite selenite crystals (p. 118).

Occurrence. In the Lower Devonian Sediments, Michigan, U.S.A.¹; in Miocene sands and marls, Iraq and Iran²; in oil-well samples, Egypt³; in sands of the Kettleman Hills, California, U.S.A.⁴.

Later Records. In Permo-Triassic deposits of S. Cumberland and Furness⁵.

Possible Sources of Derivation. Invariably authigenic; occurs mainly in association with limestones from which it can be formed by replacement (metasomatism). Also occurs with rock-salt and, contrary to usual belief, co-exists with gypsum in the same deposit.

REMARKS.—Haloanhydrite is a peculiar species compounded of rock-salt and anhydrite.

References

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² Author's observations.

³ T. S. Bowman, Report on Boring for Oil in Egypt, Section iii, *Mines and Quarries Dept., Egypt*, 1931.

⁴ M. N. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, **18**, 1934, p. 1559.

⁵ K. C. Dunham and W. C. C. Rose, *Proc. Geol. Assoc.*, **60**, 1949, p. 25.

General Reference

L. Cayeux, *Introduction à l'Étude Pétrographique des Roches Sédimentaires*. 2nd ed., Paris, 1931.

ANKERITE

[Pl. 7A, between pp. 48–49]

Chem. Comp. CaO . (Mg, Fe)O . 2CO₂.

System. Trigonal.

Habit. Rhombohedral, often curved.

Structure. Crystalline or massive.

Cleavage. Perfect || (10 $\bar{1}$ 1).

Fracture. Irregular, rare.

Hardness. 3–4.

Spec. Grav. 2.95–2.97.

Lustre. Vitreous, pearly.

Colour. White, yellow, brown.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. varies with FeCO_3 content, low for ϵ , high for ω . FeCO_3 , 10%, $\omega = 1.698$, $\epsilon = 1.518$; FeCO_3 , 22%, $\omega = 1.716$; $\epsilon = 1.526$. Birefringence very strong, $\omega - \epsilon = 0.180$, 0.190. Optically uniaxial, negative. (10 $\bar{1}$ 1) cleavage flakes show partial interference figure.

Characters in Sediments. Occurs usually in irregular, often curvilinear, rhombohedral grains, white to brown in colour and with marked R.I. variations. Diagnosed chiefly by these characteristics, also strong 'twinkling' effect on rotation of polarizer alone. It is desirable to confirm diagnosis by chemical tests for ferrous carbonate content.

Occurrence. In the Northumberland coalfield¹; in the Lower Argovian limestones and Upper Bajocian, Jura, Switzerland².

Later Records. In Millstone Grit, Bodorgan, Anglesea³; in Northampton Sand Ironstone Field⁴; in residual deposits, Mantok district, N.W. Banka, Indonesia⁵.

Possible Sources of Derivation. From sedimentary rock masses, either as primary or secondary constituent.

References

- ¹ L. Hawkes and J. A. Smythe, *Mineral. Mag.*, **24**, 1935, p. 65.
- ² A. Heim, *Beitr. geol. Karte Schweiz*, **50**, 1916.
- ³ F. Smithson, *Geol. Mag.*, **91**, 1954, p. 180.
- ⁴ J. H. Taylor, *Mem. Geol. Surv.*, 1949, p. 3.
- ⁵ J. W. A. Bodenhausen, *Proc. Konink. Nederl. Akademië van Wetenschappen, Amsterdam*, Series B, **52**, 1954, p. 322.

ANORTHITE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$.

System. Triclinic.

Habit. Tabular, prismatic, commonly twinned on Albite law (101); also Pericline law (about b axis). Carlsbad law (about c axis); Baveno law (021) or Manebach law (001).

Structure. Crystalline.

Cleavage. Perfect \parallel (001), imperfect \parallel (010), rarely \parallel (110). Parting \parallel (100).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 2.77.

Lustre. Vitreous, pearly.

Colour. White

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.576$, $\beta = 1.584$, $\gamma = 1.588$. Birefringence moderate, $\gamma - \alpha = 0.012$. Optically biaxial, negative. $2V = 77^\circ$, $2E = 163^\circ$. Oblique extinction. $Bxa = X' \wedge (001) = 37^\circ$, $\wedge (010) = 40^\circ$. Dispersion weak, $\rho > \nu$.

DIAGNOSTIC PROPERTIES

Characters in Sediments. Detrital anorthite is extremely rare in sediments, being easily altered to 'saussurite', a complex mixture of zoisite, epidote, albite, quartz, calcite, etc. Diagnosis depends on determination of definite crystal faces presented by grains and on careful measurements of optical properties thereon. The R.I. is higher than Canada balsam, which distinguishes anorthite from albite and oligoclase. Grains inclined to be irregular, generally clear, though with inclusions, e.g. iron ores, zircon. Where twin lamellæ are visible (as is usual) these form broad bands and serve as a useful guide to identity by measurement of extinction angle (37° – 40°) therefrom.

Occurrence. In the soils of Kedivi, Java¹.

Possible Sources of Derivation. Basic and ultrabasic igneous rocks.

Reference

¹ G. A. Neeb, *Overdruk uit de Handelingen v/h. 7^{de} Ned. Ind. Natuurwetenschappelijk Congres*, 1936, p. 695.

ANORTHOCLASE

(FELSPAR GROUP)

[Pl. 7B, between pp. 48-49]

Chem. Comp. (Na, K)₂O . Al₂O₃ . 6SiO₂.

System. Triclinic.

Habit. Prismatic or tabular || (010). Twinning on Carlsbad, Baveno and Manebach laws. Multiple twinning common.

Structure. Crystalline.

Cleavage. Perfect || (010) and (001).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 2.58.

Lustre. Vitreous, pearly.

Colour. White.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha \approx 1.519$, $\beta \approx 1.525$, $\gamma \approx 1.527$. Birefringence weak, $\gamma - \alpha \approx 0.008$. Optically biaxial negative. Optic axial plane \perp (010). *Bxa* X inclined at 6° to 12° to α in (010). Extinction on (001) 1° to 6° . $2V = 45^{\circ}$. $2E \approx 71^{\circ}$. Dispersion weak, $\rho > \nu$.

Characters in Sediments. In detrital sediments identification of anorthoclase depends largely on grains exhibiting a combination of albite and microcline twinning, in which the former appear as extremely fine, narrow bands. The result is what A. N. Winchell terms a 'quadrille structure'—an extremely fine 'cross hatching' which is quite distinctive. Alteration to sericite and kaolinite is a common tendency. The very low extinction angle on (001) flakes is characteristic and differs from microcline which is higher (15°). Compound grains intergrown with sanidine (p. 156) may be anticipated.

Occurrence. In the Jurassic Fuller's Earth from Combe Hay, near Bath, Somerset; in the Cretaceous Fuller's Earth of Nutfield, Surrey

and Woburn, Bedfordshire (anorthoclase with some amount of lime)¹. Later Tertiary deposits, E. England².

Possible Sources of Derivation. Soda-bearing, volcanic rocks.

REMARKS.—Compare with *microcline*, p. 143, and *orthoclase*, p. 155.

References

¹ E. F. Newton, *Proc. Geol. Assoc.*, **48**, 1937, p. 188 and Pl. 14.

² I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 336.

ANTIGORITE

(CHLORITE GROUP)

Chem. Comp. $3\text{MgO} \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic or ?Orthorhombic. Pseudoisometric.

Habit. Fibrous; often pseudomorphous.

Structure. Lamellar, massive, fibrous, 'net-like'.

Cleavage. Pseudoisometric forms with perfect (001), (010) and less perfect (100) cleavages.

Fracture. Irregular, acicular.

Hardness. 4–5.

Spec. Grav. 2.6.

Lustre. Silky.

Colour. Green, greyish yellow.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.490$, $\beta = 1.502$, $\gamma = 1.511$. Birefringence moderate, $\gamma - \alpha = 0.021$; also $\alpha = 1.560$, $\beta = 1.570$, $\gamma = 1.571$ (*A. N. Winchell*). Birefringence moderate, $\gamma - \alpha = 0.011$. Optically biaxial, negative. Optic axial plane \parallel (010). $Bxa \perp$ (001). Lamellæ have positive elongation. $Z \parallel b$. $X \parallel c$. Dispersion weak, $\rho > \nu$. Faint pleochroism sometimes noted in thick flakes: $X =$ pale yellow-green, $Y, Z =$ pale green.

Characters in Sediments. Detrital antigorite is extremely variable in appearance in sediments and is difficult of diagnosis unless physical and optical characters are critically determined. Colour, S.G., lamellar character, R.I. and positive elongation of lamellæ serve as a guide, as does the weak pleochroism if developed. May sometimes be confused with chrysotile (p. 83) which tends to a fibrous habit, but the latter is optically positive and has weaker birefringence.

Occurrence. In bore-hole samples from the plain of the River Po, Italy¹.

Possible Sources of Derivation. Ultrabasic igneous rocks (peridotites and serpentines); also as alteration product of olivine, pyroxene, amphibole etc.

REMARKS.—Antigorite *per se* is rarely recorded from detrital sediments, the wider term 'serpentine' usually designating an occurrence generally of chrysotile (p. 83), less commonly antigorite. Antigorite is decomposed by HCl, so if anticipated must be searched for in the natural untreated sample. It floats in bromoform unless associated with much

iron ore. *Bastite* is a variety of antigorite usually pseudomorphous after rhombic pyroxene (e.g. enstatite, p. 101), but it may also replace diopside (p. 96).

Reference

- ¹ I. Chelussi, *Boll. Soc. geol. ital.*, 30, 1911, p. 167.

APATITE

[Pl. 8A, B, between pp. 48-49]

Chem. Comp. Fluor - Apatite, $\text{Ca}_5(\text{CaF})(\text{PO}_4)_3$. Chlor - Apatite, $\text{Ca}_4(\text{CaCl})(\text{PO}_4)_3$. Intermediate compounds occur with both F and Cl. Also traces of Mn, Di, Ce, As and Hydroxyl.

System. Hexagonal.

Habit. Prismatic, bipyramidal or with basal pinacoid.

Structure. Usually crystalline, sometimes acicular, massive, granular or compact.

Cleavage. Imperfect $\parallel (0001)$; more rarely $\parallel (10\bar{1}0)$.

Fracture. Uneven, conchoidal.

Hardness. 5. Less in massive varieties (4.5).

Spec. Grav. 3.17-3.23.

Lustre. Vitreous to sub-resinous.

Colour. Commonly white, colourless or shades of green. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Weak conductor.

Opt. Prop. R.I. high, $\omega = 1.649$, $\epsilon = 1.644$. Birefringence weak, $\omega - \epsilon = 0.005$. Optically uniaxial, negative. Sometimes exhibits pseudo-biaxial figure with $2E > 10^\circ$. Some coloured varieties weakly pleochroic, $\epsilon > \omega$. Straight extinction. Length fast. Basal sections isotropic.

Characters in Sediments. Rounded elongated prismatic or 'egg-shaped' grains most common, sometimes with minute indeterminate inclusions arranged \parallel principal axis: these may be fluid. Grains frequently very small, often showing evidence of solution. Some varieties exhibit dark purple, pleochroic cores or nuclei: see general references, p. 48.

Occurrence. In the Old Red Sandstone, Cardiff area¹; in certain Palæozoic rocks of the English Midlands²; in the Devonian rocks of the Torquay district³; in the Old Red Sandstone of the West Midlands⁴; in the Permo-Triassic rocks of the Midlands⁵; in the Lower Permian rocks of North England⁶; in the Bunter Pebble Bed, West of England⁷; in the Upper Lias-Inferior Oolite of the West of England⁸; in the Cretaceous Fuller's Earth, Surrey⁹; in the Upper Greensand of the Haldon Hills, Devon¹⁰; in the Cretaceous Greensand of Farmingdale, New Jersey¹¹; in the Senonian Stage near Doullens, France¹²; in the Bagshot Beds of Essex¹³; in the Suffolk Boxstones, England¹⁴; in the later Tertiary deposits of East England¹⁵; in the Dartmoor detritals¹⁶; in the surface deposits of S.E. Devonshire¹⁷.

Later Records. In Fell Sandstones, Lower Carboniferous, Northumberland¹⁸; in Cementstone Group, Lower Carboniferous, Northumberland²⁰; in St. Bees Sandstone, S. Cumberland and Furness²¹; in

Lower Greensand, E. Kent²²; in Fuller's Earth, W. Weald²³; in Beach Sand, Carbis Bay, Cornwall²⁴.

Possible Sources of Derivation. Igneous rocks, especially granites and syenites.

REMARKS.—Apatite is probably far commoner in sediments than existing records would lead one to believe. It is liable to be lost by solution, either natural or during acid-cleaning of the sediment prior to separation, while its possible confusion with other colourless minerals is not an insignificant factor. The detrital form, R.I., weak birefringence, all serve to differentiate the species, though a confirmatory test for phosphate should always be resorted to where a number of grains occur whose identity as apatite is suspected, but whose diagnosis by microscopical means alone is not positive.

Apatite found in sediments is normally fluorapatite with only a small amount of chlorine; chlorapatite is comparatively rare.

For discussion of corrosion, stability and secondary growths of apatite, see papers by F. Smithson (*General References*, marked †).

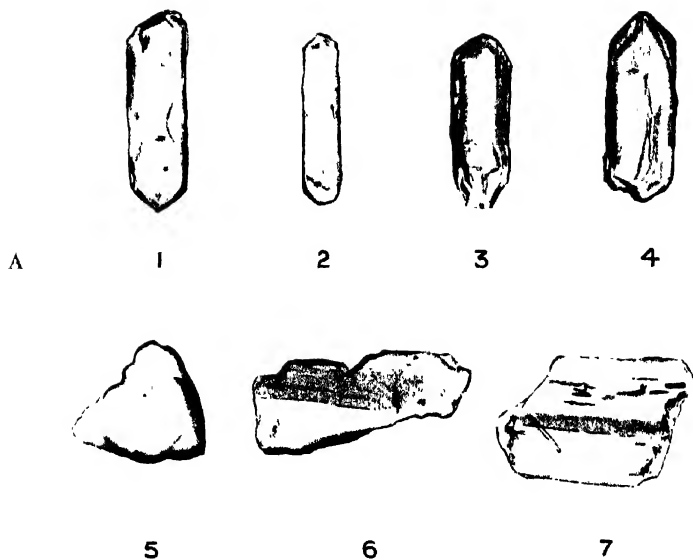
Phosphorite is a natural phosphate and may be regarded as the amorphous, fibrous or concretionary form of apatite. It usually develops from organic remains (animal excreta) interacting with calcite, e.g. coral limestone on desert islands. Recorded by P. G. H. Boswell¹⁸.

References

- ¹ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 501.
- ² W. F. Fleet, *Geol. Mag.*, **62**, 1925, p. 102, 106, 110, 113, 120, 123.
- ³ W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 141.
- ⁴ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 513.
- ⁵ W. F. Fleet, *Proc. Geol. Assoc.*, **38**, 1927, p. 1.
- ⁶ H. C. Versey, *Proc. Yorks. Geol. Soc.*, **20**, 1925, and *Geol. Mag.*, **61**, 1924, p. 380.
- ⁷ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 621.
- ⁸ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 257.
- ⁹ E. F. Newton, *Proc. Geol. Assoc.*, **48**, 1937, p. 180 and Pl. 15.
- ¹⁰ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ¹¹ S. J. Diller, *U.S. Geol. Surv., Bull.* 150, 1898, p. 1.
- ¹² H. Lasne, *Bull. Soc. géol. France*, **18**, Series 3, 1890, p. 441.
- ¹³ S. W. Wooldridge, *Proc. Geol. Assoc.*, **35**, 1924, p. 359.
- ¹⁴ P. G. H. Boswell, *Geol. Mag.*, **52**, 1915, p. 250.
- ¹⁵ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 338.
- ¹⁶ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 39.
- ¹⁷ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 147.
- ¹⁸ P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, **13**, 1923, p. 268.
- ¹⁹ D. A. Robson, *Quart. Journ. Geol. Soc.*, **112**, 1956, p. 254.
- ²⁰ ——— *ibid.*
- ²¹ K. C. Dunham and W. C. C. Rose, *Proc. Geol. Assoc.*, **60**, 1949, p. 27.
- ²² G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- ²³ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
- ²⁴ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General References

W. Mackie, The Apatites in Sedimentary Rocks as Indicators of the amount of Atmospheric Carbonic Acid in the Periods of Deposit, *Trans. Geol. Soc. Glasgow*, **17**, 1926, p. 407.



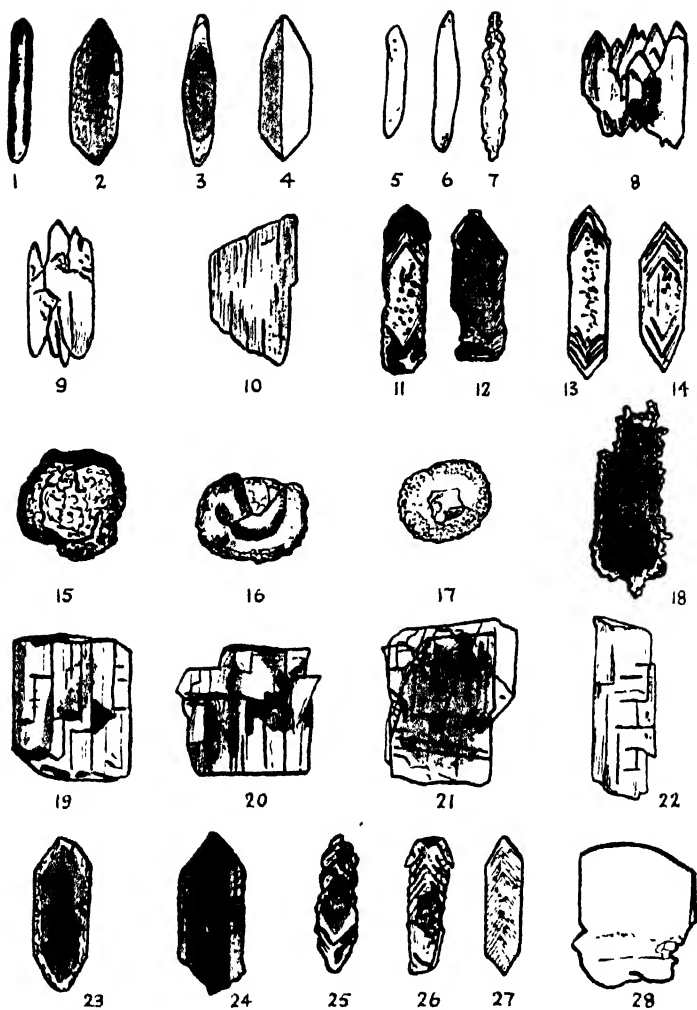
A. ANDALUSITE

- 1-4 Phiocene Sands, Cornwall
 5 Blown Sands, Newgate, Pembrokeshire
 6, 7 Phiocene Sands, Cornwall [All x 60]



B, C. ANDESINE

- B 1 Torridon Sandstone, Skye, N B [x 30.]
 Abbotsbury Iron Ore (Coralhian), Abbotsbury, Dorset [x 20]
 C Brahmputra Sands, India [x 42]
 (All x Nicols)

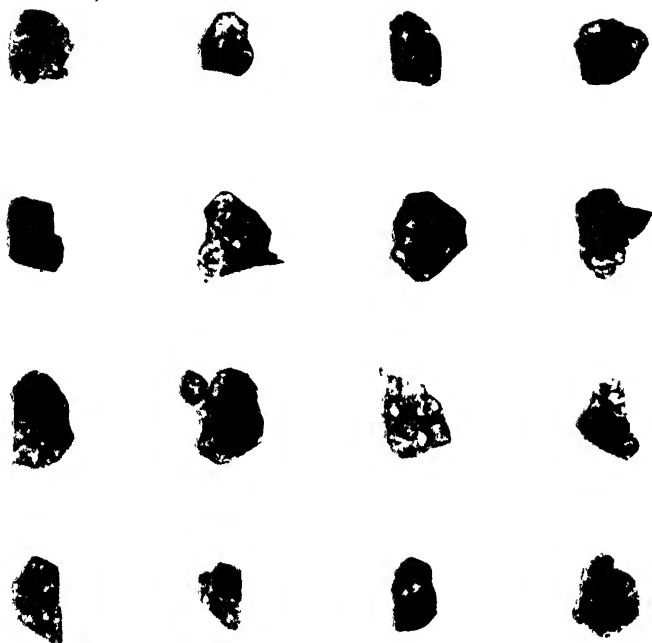


ANHYDRITE.

All from the Lower Fars (Miocene) of Iraq and Iran

- 1 4 Euhedra 5 7 "Denticular" types
 8 9 Composite "sheaf" type 10 Fibrous type
 11 14 Zoned types 15 17 "Oolite" types
 18 "Latched" or "ragged" type.
 19 21 Rectangular (Pseudo-cubic cleaved) types
 22 "Kyanite" type 23 24 With dark cores
 25 27 "Herring-bone" type 28 Glass-clear gram [All $\times 25$]

N.B. Nos. 10, 14, 18, 25-27 show partial alteration to gypsum



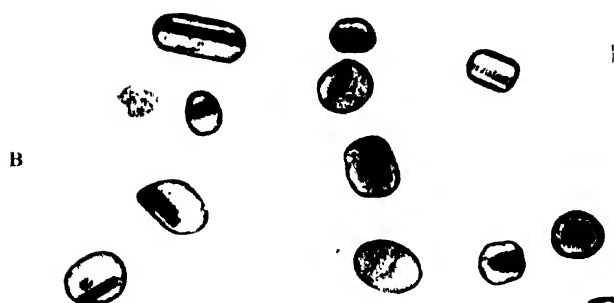
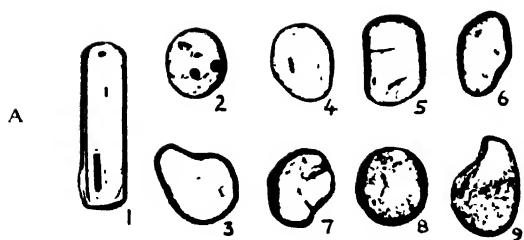
A. ANKERITE.
Anglesey [x 40]



2

B. ANORTHOCLASI

- 1 Fuller's Earth (Aptian), Nutfield, Surrey. *Note* Associated with feldspar and pyrite [x 35]
- 2 Fuller's Earth (Aptian), Nutfield, Surrey [x 50]



A, B. APATITE.

- A 1-3 Shore Sand, Co. Dublin [x 65]
 4-9 Trias, Yorkshire [x 65]
 B Cored Apatite, Trias, Yorkshire [x 50]

W. F. Fleet and F. Smithson, On the Occurrence of Dark Apatite in some British Rocks, *Geol. Mag.*, **65**, 1928, p. 6.

A. W. Groves and A. E. Maurant, Inclusions in the Apatites of some Igneous Rocks, *Mineral. Mag.*, **22**, 1929, p. 92.

B. Simpson, The Dusky Apatites of the Eskdale (Cumberland) Granite, *Geol. Mag.*, **70**, 1933, p. 375.

† F. Smithson, *Proc. Geol. Assoc.*, **42**, 1931, p. 125.

† *Geol. Mag.*, **78**, 1941, p. 97.

† *Quart. Journ. Geol. Soc.*, **98**, 1942, p. 27.

ARAGONITE

[P1. 9A, between pp. 64–65]

Chem. Comp. CaCO_3 .

System. Orthorhombic.

Habit. Euhedral, acicular and as interpenetration twins resulting in pseudo-hexagonal 'platy' forms.

Structure. Crystalline, globular, earthy.

Cleavage. Good \parallel (010); imperfect \parallel (110) and (011).

Fracture. Subconchoidal.

Hardness. 3.5–4.

Spec. Grav. 2.93–2.95.

Lustre. Vitreous, resinous on fractured surfaces.

Colour. Colourless, grey, greyish-yellow, green, mauve.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. both lower and higher than Canada balsam, as in calcite, $\alpha = 1.530$, $\beta = 1.680$, $\gamma = 1.685$. Birefringence very strong, $\gamma - \alpha = 0.155$. Optically biaxial, negative. Optical axial plane \parallel (100). $Bxa = X \parallel c$, \perp (001); $Z \parallel b$. Length fast. Optic axial angle small, $2V = 18^\circ$, $2E = 30^\circ$. Weak dispersion, $\rho < \nu$. Straight extinction in prismatic grains. Non-pleochroic. Characteristic 'twinkling' as in calcite.

Characters in Sediments. Detrital aragonite is extremely rare and the irregularly-shaped fragments met with in certain sediments are usually ascribable to broken lamellibranch shells or possibly gastropod remains. The porcellaneous forms of *foraminifera* are mainly of aragonite. Otherwise it is difficult to be certain of definite diagnosis of this mineral by microscopical means alone and chemical tests are desirable if possible, chiefly to distinguish it from calcite (see Remarks below).

Occurrence. In certain typical sediments from the Upper Cretaceous of Maryland, U.S.A.¹; in the North Sea Drift and Upper Glacial Brickearths of East Anglia²; in the modern Fenland Silt on the north-west coast of the Wash, near Friskney³; in the mud-deposits of the 'limans' of Kuyabuik, near Odessa, Russia⁴; as fragments of probable organic origin in many Tertiary and Recent deposits, e.g. Pliocene of Walton-on-Naze, Essex⁵.

Possible Sources of Derivation. Where not of organic origin almost certainly authigenic and associated with limestone and gypsum; also

occurs in vesicles in basalts and various lavas to which it may be locally traced in some instances.

REMARKS.—Aragonite is distinguished from calcite by its higher S.G. and absence of rhombohedral cleavage; also by Meigen's reaction:—boil grains with $\text{Co}(\text{NO}_3)_2$ when a lilac or violet colour quickly appears. Another test is to treat the $\text{Co}(\text{NO}_3)_2$ stained grains with ammonium sulphide solution, when cobalt sulphide is precipitated on the aragonite grains more thickly than on any associated calcite grains, resulting in dense black aggregates on the former species.

References

- ¹ M. I. Goldman, *Maryland Geol. Surv.*, 1916, p. 111.
- ² P. G. H. Boswell, *Proc. Geol. Assoc.*, 27, 1916, p. 79.
- ³ F. Hardy, *Geol. Mag.*, 57, 1920, p. 543.
- ⁴ M. Sidorenko, *Zap. novoruss. obschch. vestestvoisp.*, 21, 1897, p. 118.
- ⁵ Author's observations.

ARFVEDSONITE

(AMPHIBOLE GROUP)

Chem. Comp. $5\text{Na}_2\text{O} \cdot 2\text{CaO} \cdot 14\text{MgO} \cdot 3\text{Al}_2\text{O}_3 \cdot 30\text{SiO}_2 \cdot 2\text{TiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Long prisms or 'blades' ||c.

Structure. Crystalline, fibrous.

Cleavage. Perfect || (110) at 124° .

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.33–3.45.

Lustre. Vitreous.

Colour. Blue, black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.670$, $\beta = 1.680$, $\gamma = 1.682$. Birefringence moderate, $\gamma - \alpha = 0.012$. Optically biaxial, negative. Optic axial plane and Z \perp (010). Elongation of prism negative. Extinction angle $X \wedge c = 14^\circ$ to $+20^\circ$; $Z \wedge c = 20^\circ$ – 25° . Y \perp b. Optic axial angle variable about X. Pleochroism strong, X = dark green > Y = pale brown > Z = black. Strong dispersion.

Characters in Sediments. Detrital arfvedsonite is characterized by its tendency to occur in blue or bluish green fibrous or prismatic grains, having distinctive pleochroism and relatively high extinction angle compared with hornblende, actinolite or riebeckite; also such extinction is generally incomplete owing to strong dispersion of bisectrices. Incipient or nearly complete alteration to siderite and limonite may be noted.

Occurrence. In the North Sea Drift and Upper-Glacial Brick-Earths of East Anglia¹; in surface deposits, gravels of present and ancient river systems and plateau gravels of Cambridgeshire²; in the modern Fenland Silt of the north-west coast of the Wash, near Friskney³; in the sands on the south shore of Long Island and the coast of New Jersey⁴;

in association with dolomite in a trench cut at Fulford, East Yorkshire⁵; in shore sand, S. Coast Greenland⁶.

Possible Sources of Derivation. Soda-bearing igneous rocks, *e.g.* nepheline-syenite.

References

- ¹ P. G. H. Boswell, *Proc. Geol. Assoc.*, **27**, 1916, p. 79.
- ² R. H. Rastall, *Proc. Cambridge Phil. Soc.*, **17**, 1913, p. 132.
- ³ F. Hardy, *Geol. Mag.*, **57**, 1920, p. 543.
- ⁴ R. J. Colony, *Journ. Sed. Pet.*, **2**, 1932, p. 150.
- ⁵ S. Melmore, *Naturalist*, 1929, p. 341.
- ⁶ R. D. Crommelin, *Meddelelser om Grønland*, **113**, 1937.

ARSENOPYRITE

(MISPICKEL)

[Pl. 9B, between pp. 64-65]

Chem. Comp. FeAsS.

System. Monoclinic.

Habit. Prismatic (001), less common (010); often twinned.

Structure. Crystalline, granular.

Cleavage. Good || (101), trace || (010).

Fracture. Irregular.

Hardness. 5.5-6.

Spec. Grav. 5.9-6.2.

Lustre. Metallic.

Colour. Silver-white to grey. Opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Good conductor.

Opt. Prop. In very thin grains anisotropic with weak pleochroism.

Characters in Sediments. A difficult species to identify as detrital grains, unless suspected because of special environmental circumstances.

Occurrence. In Dartmoor detritals¹.

Possible Sources of Derivation. Contact metamorphic rocks; mineral veins.

REMARKS.—Confirm if necessary by chemical spot test for arsenic.

Reference

- ¹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 47.

ASTROPHYLLITE

Chem. Comp. $4[(K, Na)_2(Fe, Mn)_4TiSi_4O_{14}(OH)_2]$.

System. Orthorhombic.

Habit. Elongated or platy.

Structure. Crystalline.

Cleavage. Perfect || (010), imperfect || (001).

Fracture. Uneven, laminæ brittle.

Hardness. 3.

Spec. Grav. 3.3–3.4.

Lustre. Submetallic, pearly.

Colour. Gold yellow, bronze.

Mag. Prop. Weakly magnetic.

Elect. Prop. —.

Opt. Prop. R.I. high, $\alpha = 1.678$, $\beta = 1.703$, $\gamma = 1.733$. Birefringence strong, $\gamma - \alpha = 0.055$. Optically biaxial, positive. Optic axial plane (001); $Z = a$. $2V = 75^\circ \pm$; $\rho > v$. Strongly pleochroic: $X > Y > Z$: X = dark golden yellow, Y = orange yellow, Z = lemon yellow.

Characters in Sediments. Occurs as distinctive golden yellow or brown platy grains resembling mica. Very rare. Differs from mica in brittleness of the laminæ, $bxc \perp (010)$ and maximum absorption \perp laminæ.

Occurrence. In shore sands, S. Coast Greenland¹.

Possible Sources of Derivation. Nepheline syenite.

REMARKS.—This rare but beautiful species is found only in vicinity of nepheline syenite and associated soda-bearing rocks which have been laid under contribution to recent deposits.

References

- ¹ R. D. Crommelin, *Meddelelser om Grønland*, 113, 1937.

General References

- J. D. and E. S. Dana, *System of Mineralogy*, 6th ed. (Wiley, New York), 1892, p. 719.
O. B. Boggild, *Meddelelser om Grønland*, 33, 1906, p. 97.

AUGITE

(PYROXENE GROUP)

[Pl. 10A, B, *between pp.* 64–65]

Chem. Comp. $\text{CaO} \cdot 2(\text{Mg, Fe})\text{O} \cdot (\text{Al, Fe})_2\text{O}_3 \cdot 3\text{SiO}_2$. Also titaniferous varieties.

System. Monoclinic.

Habit. Commonly prismatic with varying terminations; twinning on (100) common.

Structure. Usually crystalline, sometimes granular.

Cleavage. Good $\parallel (110)$, more rarely $\parallel (100)$. (001) parting frequently observed given by twin lamellæ $\parallel (100)$.

Fracture. Uneven.

Hardness. 5–6.

Spec. Grav. 3.2–3.6 (varies with composition).

Lustre. Vitreous, sometimes resinous.

Colour. Shades of yellowish-green, green to blackish-green. Sometimes brown.

Mag. Prop. Moderately magnetic; varies with the amount of iron present.

Elect. Prop. Moderately good conductor.

Opt. Prop. R.I. very high, $\alpha = 1.699$, $\beta = 1.718$, $\gamma = 1.742$. Birefringence strong, $\gamma - \alpha = 0.043$. Optically biaxial, positive. Optic axial

plane \parallel (010). $Y \parallel b$. $Bxa = Z \wedge c = 46^\circ\text{--}51^\circ$: oblique extinction $2V = 65^\circ$. † Slightly pleochroic in some titaniferous varieties with characteristic violet or red tint (Y). Dispersion $\rho > \nu$.

Characters in Sediments. Grains usually either rounded prismatic forms or irregular cleavage fragments, the latter often showing the emergence of an optic axis. Fractured or 'broken' grains are sometimes met with which are very characteristic of the particular horizon at which they occur. Diagnosed chiefly by its colour and high extinction angle and anticipated where other pyroxenes, also olivine, are prevalent.

Occurrence. In the Silurian rocks of Southern Scotland¹; in the Lower Old Red Sandstone of the Forfarshire Coast²; in the Old Red Sandstone of the West Midlands³; in the Senonian Coal-Measure clays of the Malvern Hills, New Zealand⁴; in the Permo-Triassic rocks of the Midlands⁵; in certain Boulder Clays of Yorkshire⁶; in surface and plateau gravels, Cambridgeshire⁷; in surface deposits of S.E. Devonshire⁸; in the deep sea deposits of the Atlantic Ocean⁹; in the dune sands of South Wales¹⁰; in shore sands at Rosslare, Co. Wexford¹¹; in shore sands of Cape Verde Islands¹²; in blown sand at Newgale, Pembrokeshire¹³; in the sands of the Northumberland coast¹⁴.

Later Records. In Fell Sandstones, Lower Carboniferous, Northumberland¹⁵; in Beach Sand, Granada, B.W.I.¹⁶.

Possible Sources of Derivation. Intermediate and basic igneous rocks.

REMARKS.—As would be expected, augite is somewhat haphazard in its occurrence in sediments, though it is frequently very common in deep-sea deposits and shore sands fed by disintegrated volcanic materials. Sometimes it is difficult to decide between augite and diopside in diagnosis; there is much to be said for restricting the latter label to the pale green or colourless grains found in pyroxene-rich samples the striking feature of which is often their surprising freshness, in contrast to the yellowish-green augite which frequently exhibits traces of decomposition or dusky inclusions of iron-ores. For corrosion tendencies and stability of augite, see General Reference below. See also diopside, p. 96, and ægirine, p. 30.

References

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.
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- ³ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 513.
- ⁴ S. Page, in R. Speight, *Geol. Mem. Dept. Sci. and Ind. Research*, New Zealand, **1**, 1928, p. 1.
- ⁵ W. F. Fleet, *Proc. Geol. Assoc.*, **38**, 1927, p. 6.
- ⁶ A. Raistrick, *Geol. Mag.*, **66**, 1929, p. 337.
- ⁷ R. H. Rastall, *Proc. Cambridge Phil. Soc.*, **17**, 1913, p. 132.
- ⁸ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 147.
- ⁹ J. Murray and J. Chumley, *Trans. Roy. Soc. Edinburgh*, **54**, 1924, p. 1.
- ¹⁰ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 323.
- ¹¹ Author's observations.
- ¹² Noted by G. M. Part.
- ¹³ Author's observations.

† Varies, as with other optical properties, with the amount of Al_2O_3 and Fe_2O_3 present.

¹⁴ L. Hawkes and J. A. Smythe, *Geol. Mag.*, **68**, 1931, p. 345.

¹⁵ D. A. Robson, *Quart. Journ. Geol. Soc.*, **112**, 1956, p. 254.

¹⁶ H. S. Bennett and P. Martin-Kaye, *Journ. Sed. Pet.*, **21**, 1951, p. 200.

General Reference

C. H. Edelman and D. J. Doeglas, Reliktstrukturen detritischer Pyroxene und Amphibole, *Min. Pet. Mitt.*, **42**, 1932, p. 482.

AUTUNITE

Chem. Comp. $[\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10\text{--}12\text{H}_2\text{O}]$.

System. Tetragonal.

Habit. Tabular (001).

Structure. Crystalline; foliated; scaly aggregates.

Cleavage. Perfect \parallel (001), less distinct \parallel (100).

Fracture. Uneven.

Hardness. 2–2.5.

Spec. Grav. 3.1–3.2.

Lustre. Vitreous, pearly.

Colour. Sulphur-yellow, sometimes with green tinge.

Mag. Prop. Non-magnetic.

Elect. Prop. —

Opt. Prop. R.I. low, $\omega = 1.577$, $\epsilon = 1.553$. Birefringence moderate $\omega - \epsilon = 0.024$. Optically uniaxial, negative. (Sometimes assumes abnormal biaxial negative character when $2V = 0^\circ\text{--}53^\circ$). Weakly pleochroic, $X(\epsilon) =$ colourless, $Z(\omega) =$ golden yellow.

Characters in Sediments. Usually as yellow, mica-like, platy grains, transparent to translucent.

Occurrence. In Dartmoor detritals¹.

Possible Sources of Derivation. From uraninite-bearing veins (p. 198); as an alteration product of that mineral.

REMARKS. — Autunite is a rare mineral as detrital. It can be confirmed by its strong fluorescence in ultra-violet light. (See Vol. I, Ch. XII.)

Reference

¹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 47.

AXINITE

[Pl. 10C, between pp. 64–65]

Chem. Comp. $6(\text{Ca}, \text{Fe}, \text{Mn})\text{O} \cdot 2\text{Al}_2\text{O}_3 \cdot \text{B}_2\text{O}_3 \cdot 8\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Triclinic.

Habit. Diamond- or wedge-shaped crystals, sometimes euhedral, rarely prismatic; flattened.

Structure. Crystalline, rarely lamellar or granular.

Cleavage. Distinct \parallel (010); sometimes \parallel (001) and (130).

Fracture. Conchoidal.

Hardness. 6.5–7.

Spec. Grav. 3.25–3.30.

Lustre. Vitreous.

Colour. Pinkish-brown to red, 'plum', greyish-yellow; shades of mauve and yellowish-red; rarely colourless.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.678$, $\beta = 1.685$, $\gamma = 1.688$. Birefringence moderate, $\gamma - \alpha = 0.010$. Optically biaxial, negative. Trace of optic axial plane inclined 40° to edge (111) ($1\bar{1}0$) and $24^\circ 40'$ to (111) ($1\bar{1}1$), (A. Des Cloizeaux). $Bxa = X$ practically \perp (111). Oblique extinction (111) \wedge (110) = 40° . (111) \wedge ($1\bar{1}1$) = 24° . $2V = 71^\circ 38'$ (red). Strong dispersion, $\rho < \nu$. Pleochroism moderate: X = pale green, olive green, Y = dark blue or violet, Z = brown; only observed in thick grains.

Characters in Sediments. Occurs in irregular or rounded, diamond-shaped grains of characteristic colour, usually a delicate shade of mauve or pink. The grains reveal the presence of small conchoidal fractures, which are characteristic. Detrital axinite is for the most part nonpleochroic unless the grains are large. Grains frequently fail to extinguish in any position.

Occurrence. Observed only in Recent Sands, in particular the shore sands at various points along the Land's End—St. Ives coast, Cornwall¹.

Possible Sources of Derivation. Metamorphosed basic igneous rocks (pneumatolytic modifications); cavities in granitic rocks.

REMARKS.—A local species to be anticipated in recent sediments rather than in those of greater age. Often associated with pyroxene, amphibole, calcite and sulphide ores.

Reference

- ¹ Author's observations.

BADDELEYITE

Chem. Comp. ZrO_2 .

System. Monoclinic; prismatic.

Habit. Euhedral, tabular \parallel (100); striated on (100) and sometimes (010). Often twinned on (100), frequently polysynthetic; also contact and interpenetrant twins about (110), less often (201).

Structure. Crystalline.

Cleavage. Perfect \parallel (001); imperfect \parallel (010) and (110).

Fracture. Subconchoidal, uneven; brittle.

Hardness. 6.5.

Spec. Grav. 5.4–6.02.

Lustre. Vitreous, resinous; submetallic in opaque varieties.

Colour. Yellow, brown, black, rarely colourless. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\alpha = 2.13$, $\beta = 2.19$, $\gamma = 2.20$ (all ± 0.01). Birefringence strong, $\gamma - \alpha = 0.07$ (± 0.01). Optically biaxial, negative. Optic axial plane \parallel (010). $Bxa = X$ inclined to C axis $11^\circ-13^\circ$ in obtuse angle β . $Y = b$. $2E = 70^\circ$, $2V = 30^\circ$. Oblique extinction,

10°–13°. Strong dispersion, $\rho > v$. Pleochroism distinctive: Z = red-brown, Y = deep green, X = red-brown; $X > Y > Z$.

Characters in Sediments. Usually as worn, tabular grains of characteristic appearance and colour, in recent sediments (mainly alluvial).

Occurrence. In gold washings (detrital) at Nedi, Kilo, Belgian Congo¹; in gem-gravels, Rakwana and Balangoda, Ceylon²; in diamond sands, Rio Verdinho, Matto Grosso, Brazil³.

Possible Sources of Derivation. Syenite, pyroxenite.

REMARKS.—A rare detrital mineral (*syn. Brazilite*), to be searched for in deposits rich in gem and/or rare-earth minerals in appropriate environments. Chemical confirmation essential, also X-ray spectrometer and powder methods⁴.

References

^{1,2,3} J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, pp. 608–10.

⁴ *ibid.*, ref. 3, p. 610.

BARITE

[Pl. 11A, B, between pp. 64–65]

Chem. Comp. BaSO₄.

System. Orthorhombic.

Habit. Prismatic, with basal plane strongly developed. Twinning on (100) common.

Structure. Crystalline, massive or lamellar.

Cleavage. Perfect \parallel (001) and (110); imperfect \parallel (010).

Fracture. Uneven.

Hardness. 3.

Spec. Grav. 4.5.

Lustre. Vitreous, pearly, often combined with 'cloudy' appearance.

Colour. Colourless, bluish-white or yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.636$, $\beta = 1.637$, $\gamma = 1.648$. Birefringence moderate, $\gamma - \alpha = 0.012$. Optically biaxial, positive. Optic axial plane \parallel (010). Length slow. $Bxa = Z \perp (100)$. $2V = 37^\circ 30'$. $X \parallel c$, $Y \parallel b$, $Z \parallel a$. Prismatic grains give straight extinction. Cleavage grains may show emergence of the *bxo*. Dispersion weak, $\rho < v$.

Character of Sediments. Fragments of this mineral are varied in character; the normal type is entirely irregular, angular and determined chiefly by fracture, cleavage or the original shape of the interstice which it filled as a cementing medium. Sharply angular cleavage fragments are common, but seldom yield good interference figure. Grains rarely show rounding, though they may be intensely fractured. Diagnosed chiefly by its high S.G. and optical properties, also by its 'patchy' lustre, brown staining and varied inclusions (iron-ores).

Occurrence. In the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian and Triassic rocks of the English Midlands¹;

in the Ordovician rocks of Carnarvonshire²; in the Old Red Sandstone of the West Midlands³; in the Old Red Sandstone of the Cardiff district⁴; in the Lower Carboniferous sandstones of West Cumberland⁵; in the Millstone Grit of Yorkshire⁶; in the Coal-Measure Clay, Seaton, Northumberland⁷; in the Permo-Triassic rocks of the Midlands⁸; in the Lower-Permian rocks of Northern England⁹; in all areas where sandstones of Triassic age occur, *e.g.* Cheshire, Staffordshire, Nottinghamshire, Devonshire etc.¹⁰; in the Keuper Marls around Charnwood¹¹; in the New Red Sandstone of West England¹²; in the New Red Rocks of the Quantock Hills¹³; in the Fuller's Earth and Folkestone Beds (Lower Greensand) of Surrey and Kent respectively¹⁴; in the Lower London Clay at Sheppey¹⁵; in the river sand from the Ure and Ouse¹⁶; in shore sands from Co. Cork, Eire¹⁷; in the sands of the Northumberland Coast¹⁸.

Later Records. In Magnesian Limestone, South Durham¹⁹; in Fuller's Earth, Western Weald²⁰.

Possible Sources of Derivation. From sandstones in which it acts as the cementing medium; from veins in limestones associated with calcite; from the gangue of metalliferous veins or from massive deposits of barite associated with calcareous sediments.

REMARKS.—Rarely met with as detrital grains; H. C. Versey has described both authigenic and allogenic occurrences; presence in residue usually due to the disintegration of the cementing medium of a sand on treatment of the latter for 'heavy' mineral analysis. F. Smithson has found euhedral authigenic barite in Devonian limestone in Anglesea (personal communication 1958). Distinguish from anhydrite by the forms and cleavages of that mineral. Barite has the higher S.G. and the characteristic lustre noted above.

References

- ¹ W. F. Fleet, *Geol. Mag.*, **62**, 1925, p. 98.
- ² S. A. Billingham, *Geol. Mag.*, **66**, 1929, p. 289.
- ³ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 512.
- ⁴ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 489.
- ⁵ H. P. Lewis, *Geol. Mag.*, **68**, 1931, p. 543.
- ⁶ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 251.
- ⁷ W. M. Hutchings, *Geol. Mag.*, 1890, pp. 264, 316.
- ⁸ W. F. Fleet, *Proc. Geol. Assoc.*, **38**, 1927, p. 6.
- ⁹ H. C. Versey, *Proc. Yorks. Geol. Soc.*, **20**, 1925, p. 200.
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- ¹¹ T. O. Bosworth, *Quart. Journ. Geol. Soc.*, **68**, 1912, p. 281.
- ¹² H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 234.
- ¹³ H. H. Thomas, *Mem. Geol. Surv.*, Great Britain Sheet 295, 1908, p. 60.
- ^{14, 15} G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, p. 93.
- ¹⁶ S. Melmore, *Geol. Mag.*, **63**, 1926, p. 268.
- ¹⁷ Author's observations.
- ¹⁸ L. Hawkes and J. A. Smythe, *Geol. Mag.*, **68**, 1931, p. 345.
- ¹⁹ A. Fowler, *Proc. Geol. Assoc.*, **67**, 1956, p. 253.
- ²⁰ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

General Reference

- J. M. Sweet, Notes on British Barytes, *Mineral Mag.*, **22**, 1930, p. 357.

BARKEVICITE

(AMPHIBOLE GROUP)

Chem. Comp. Between hornblende (p. 123) and arfvedsonite (p. 50); variety of hornblende rich in Fe and alkalis.

System. Monoclinic.

Habit. Prismatic, fibrous.

Structure. Crystalline.

Cleavage. Perfect \parallel (110).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.43.

Lustre. Vitreous.

Colour. Green, greenish brown to black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.687$, $\beta = 1.707$, $\gamma = 1.708$. Birefringence moderate, $\gamma - \alpha = 0.021$. Optically biaxial, negative. Oblique extinction, $Z \wedge c = 12^\circ$ to 14° . $X = b$. Length slow. $2V = 54^\circ$. $2E = 102^\circ$. Pleochroism distinctive: $X =$ brown yellow $> Y =$ reddish brown $> Z =$ deep brown.

Characters in Sediments. Prismatic or irregular (010) grains determined by cleavage, having distinctive green colour and pleochroism. Differs from hornblende chiefly in pleochroism and generally smaller extinction angle; from arfvedsonite in pleochroism and larger extinction angle of that species.

Occurrence. In the Dune Sands of South Wales¹.

Possible Sources of Derivation. Alkaline intermediate igneous rocks, e.g. nepheline-syenite.

Reference

¹ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 331; *Proc. Swansea Sci. and Field Nat. Soc.*, **1**, 1927, p. 16.

BASALTINE, BASALTIC HORNBLLENDE

(AMPHIBOLE GROUP)

Chem. Comp. $3CaO \cdot Na_2O \cdot 7(Mg, Fe)O, 3(Al, Fe)_2O_3, TiO_2, 12SiO_2, 2H_2O$.

System. Monoclinic.

Habit. Prismatic \parallel c. Lamellar twinning about (100).

Structure. Crystalline, massive.

Cleavage. Perfect \parallel (110). Less distinct \parallel (100) and (010). Cleavage traces in cross sections \perp . prism zone intersect at 124° . Parting in twin crystals \parallel (100) and (010).

Fracture. Uneven, subconchoidal.

Hardness. 6.

Spec. Grav. 3.18.

Lustre. Vitreous.

Colour. Brown to black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.670$, $\beta = 1.683$, $\gamma = 1.693$. Birefringence moderate, $\gamma - \alpha = 0.023$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. Length and cleavage trace slow. $Y = b$. Oblique extinction. $Z \wedge c = 9^\circ$, smaller in many examples ($1^\circ - 2^\circ$). $Bxa = X$ inclined at low angle to \perp of (100) . $2V = 83^\circ$. Dispersion small, $\rho > \nu$. Pleochroism variable: $Z =$ dark olive green or brown $> Y =$ dark brown $> X =$ pale yellow.

Characters in Sediments. Basaltine occurs in sediments in similar form of grains to ordinary hornblende. It is identified by colour, usually brownish yellow, deep brown or almost opaque, prismatic cleavage, very low extinction angle (almost straight in many examples), and distinctive pleochroism. Basaltine has a higher specific gravity and R.I. than common hornblende. Inclusions generally iron ores, sometimes magnetite; also zircon, apatite and glass. Grains are usually fresh, showing little tendency to decomposition products.

Occurrence. In Eocene Sandstones etc., of West Central Italy¹; in the Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California²; in the Limburg Loess³; in the Mediterranean deep sea deposits⁴; in the soils of Java⁵; in sands of the Kettleman Hills, California, U.S.A.⁶.

Possible Sources of Derivation. Volcanic lavas.

REMARKS.—Formed essentially by the oxidation of the iron in ordinary hornblende, hence the synonym 'oxyhornblende'.

References

¹ L. Maddalena, *C.R. Intern. Géol. Congr.*, 13th Session, 1922, iii (1926), p. 1309.

² R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, **11**, 1927, p. 363.

³ J. H. Druif, Over het ontstaan der Limburgsche Löss in verband met Haar mineralogische samenstelling, 1927, *Utrecht*.

⁴ I. Chelussi, *Boll. Soc. geol. ital.*, **31**, 1912, p. 79.

⁵ H. Loos, Bijdrage tot de kennis van eenige bodem soorten van Java en Sumatra. *Wageningen*, 1924.

⁶ M. N. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, **18**, 1934, p. 1559.

BASTITE

(See Antigorite, p. 46, Diopside, p. 96, and Enstatite, p. 101.)

BEIDELLITE

(MONTMORILLONITE-BEIDELLITE SERIES)*

Chem. Comp. $Al_2O_3 \cdot 3SiO_2 \cdot nH_2O$.

System. ?Orthorhombic.

Habit. Laminated.

Structure. Crystalline.

* See D. Carroll, Ch. III.

Cleavage. Perfect \parallel (001).

Fracture. ?

Hardness. Soft.

Spec. Grav. 2.58–2.62.

Lustre. Pearly.

Colour. Colourless.

Mag. Prop. ?

Elect. Prop. ?

Opt. Prop. R.I. low, $\alpha = 1.495$, $\beta = 1.537$, $\gamma = 1.537$. Birefringence strong, $\gamma - \alpha = 0.042$. Optically biaxial, negative. $X = c$. Optic axial angle small.

Characters in Sediments. Occurs in flat platy or laminated grains, resembling mica. Usually these plates yield a good biaxial negative interference figure.

Occurrence. In the underclays of Illinois Coal, U.S.A.¹.

Possible Sources of Derivation. Clays; bentonite.

REMARKS.—Beidellite is a member of a series of hydrated aluminous silicates characteristic of certain finely divided sediments such as clays. This series includes *montmorillonite* (p. 147), *nontronite* (p. 151), *rillonite* etc. According to R. E. Grim, however, beidellite is not a specific mineral, but an interlayered mixture of illite (p. 128) and montmorillonite (p. 147); it has been suggested that the term be dropped. See also M. H. Hey (references below).

Reference

¹ V. T. Allen, *Journ. Amer. Ceram. Soc.*, **15**, 1932, p. 564.

General References

C. S. Ross and E. V. Shannon, The Chemical Composition and Optical Properties of Beidellite, *Journ. Washington Acad. Sci.*, **15**, 1925, p. 467.

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M. H. Hey, *An Index of Mineral Species, etc.*, 1950, p. 126.

R. E. Grim, *Clay Mineralogy* (McGraw-Hill, New York), 1953, p. 39.

BENITOITE

Chem. Comp. $\text{BaO} \cdot \text{TiO}_2 \cdot 3\text{SiO}_2$.

System. Trigonal.

Habit. Pyramidal, tabular.

Structure. Crystalline.

Cleavage. Imperfect \parallel (10 $\bar{1}$ 1).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.65.

Lustre. Vitreous.

Colour. Blue, purple, sometimes colourless; liable to vary in same crystal.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\epsilon = 1.804$, $\omega = 1.757$. Birefringence strong, $\epsilon - \omega = 0.047$. Optically uniaxial, positive. Length slow. Straight extinction. Pleochroism distinctive: ω = colourless, ϵ = purple, indigo or greenish-blue.

Characters in Sediments. Benitoite is an extremely rare and local mineral, described from sediments in the San Benito River (head waters) area, California, U.S.A. It occurs in distinctive blue grains having characteristic optical properties (as above), especially marked blue or greenish blue to colourless pleochroism.

Occurrence. In the Upper Famennian Sandstone of the Devonian of the valley of the Ourthe, Belgium¹; in the Carrizo sand of South-West Texas².

Possible Sources of Derivation. Schist, serpentine, in which it occurs as veins or in geodes.

References

- ¹ J. Anten, *Ann. Soc. géol. Belg., Liège*, 51, 1928, p. B. 330.
- ² J. J. Lonsdale, M. S. Metz and M. T. Halbouty, *Journ. Sed. Pet.*, 1, 1931, p. 73.

BERYL

Chem. Comp. $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$.

System. Hexagonal, holosymmetric.

Habit. Prismatic, rarely tabular.

Structure. Crystalline; occasionally massive (columnar).

Cleavage. Imperfect $\parallel (0001)$.

Fracture. Conchoidal, uneven. Brittle.

Hardness. 7.5–8.

Spec. Grav. 2.63–2.80.

Lustre. Vitreous, resinous.

Colour. Emerald green, grass green, light blue, yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. varies: $\omega = 1.5724, 1.5785, 1.5825$; $\epsilon = 1.5673, 1.5735, 1.5761$. Birefringence weak, $\omega - \epsilon = 0.0051, 0.0050, 0.0064$. Optically uniaxial, negative. Sometimes abnormally biaxial, due to strain or twinning of orthorhombic individuals as trillings (Mallard). Basal sections may show (abnormally) division into six biaxial sectors with uniaxial centre (Lacroix). Straight extinction. Pleochroism weak: in emerald green varieties $Z(\omega)$ = yellowish green, $X(\epsilon)$ = pale green; in blue varieties $Z =$ greenish blue to colourless, $X =$ blue; in yellow varieties $Z =$ golden yellow, $X =$ reddish yellow. Some varieties show absorption $Z > X$ (Winchell).

Characters in Sediments. Generally as rolled, water-worn prismatic crystals of characteristic emerald green colour and lustre in alluvial deposits. The single grain described by H. M. E. Schurman⁴ is uniaxial negative, with R.I. about 1.58, conchoidal fracture and S.G. < bromoform.

Occurrence. In granite-talus and coarse stream material, Mourne Mountains, Co. Down, Ireland¹; in gem gravels, Ceylon²; in auriferous gravels, Sanarka River, S. Urals, U.S.S.R.³; in sands in the Hoggar district, Central Sahara⁴.

Possible Sources of Derivation. Drusy granite; granite pegmatite; mica schist; tin-bearing lodes.

REMARKS.—It is surprising that there are not more British records of beryl occurring as a detrital mineral. There may be a tendency to confuse with apatite (p. 47) but the latter is a much softer species.

References

^{1, 2, 3} C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 359, also *Gen. Ref.* below.

⁴ H. M. E. Schurmann, *Geologie en Mijnbouw* (N.W. Ser.), 18e Jaargang, 1956, p. 163.

General Reference

J. D. and E. S. Dana, *System of Mineralogy*, 6th ed. (Kegan Paul, Trench, Trübner, London), 1892, p. 408.

BIOTITE

(MICA GROUP)

[Pl. 11C, between pp. 64-65]

Chem. Comp. $K_2O \cdot 4(Fe, Mg)O \cdot 2(Al, Fe)_2O_3 \cdot 6SiO_2 \cdot H_2O$.

System. Monoclinic.

Habit. Tabular; short, almost hexagonal, prismatic crystals with well-developed basal planes. Frequently twinned on (110) in thin (001) laminae.

Structure. Irregular, but strongly laminated. Crystals rare.

Cleavage. Perfect basal (001). Parting || (010) and (111).

Fracture. Uneven.

Hardness. 2.5-3.

Spec. Grav. 2.79-3.16.

Lustre. Vitreous, resinous or dull.

Colour. Dark-green, brown to blackish-brown.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. low, $\alpha = 1.584$, $\beta = 1.648$, $\gamma = 1.648$. Birefringence strong, $\gamma - \alpha = 0.064$. Optically biaxial, negative. $Bva = X \perp (001)$; optic axial angle small in certain varieties, giving pseudo-uniaxial interference figure. $X \wedge c$ small. $Y = b$. Pleochroism varies with composition, being strongest in the deep brown facies (phlogopite): $X =$ colourless $< Y =$ brownish yellow.

Characters in Sediments. Occurs mostly as brown or yellow cleavage flakes with jagged edges; seldom worn. Pleochroic halos round crystals of zircon, xenotime, allanite, etc., enclosed in biotite are of frequent occurrence, especially in the deep brown varieties; other inclusions noted are rutile, anatase and monazite. Striations common.

Detrital flakes tend to lie with (001) in the plane of the slide, hence are non-pleochroic. Partial alteration to chloritic matter, producing a 'bleached' grain, is commonly observed. Diagnosed almost invariably by its colour, cleavage and almost uniaxial negative interference figure yielded by (001) flakes.

Occurrence. In the Devonian rocks of the Torquay district¹; in the Grindstones from the Coal Measures, Yorkshire²; in the Upper Lias—Lower Inferior Oolite sands of West England³; in Bentonite (Cretaceous) of Wyoming, U.S.A.⁴; in the Pliocene deposits of Cornwall⁵; *phlogopite* in Cornish Pliocene⁶; in the later Tertiary deposits of East England⁷; in dune sands of South Wales⁸; in Dartmoor detritals⁹; in Chalk boulders from the seafloor off the Scottish coast¹⁰; in shore sands from Dinard, Brittany and from White Sand Bay, Cornwall¹¹; in marine peat, Union Dock, Liverpool¹².

Later Records. In Fuller's Earth, W. Weald¹³.

Possible Sources of Derivation. Igneous and metamorphic rocks.

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- ² H. P. Lewis and W. J. Rees, *Geol. Mag.*, **63**, 1926, p. 13.
- ³ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 257.
- ⁴ D. F. Hewett, *U.S. Geol. Surv. Prof. Paper*, **145**, 1926, p. 1.
- ⁵ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 364.
- ⁶ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, pp. 341, 343.
- ⁸ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 323.
- ⁹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 46.
- ¹⁰ H. H. Thomas in W. Hill, *Proc. Roy. Soc. Edinburgh*, **35**, 1915, p. 263.
- ¹¹ Author's observations.
- ¹² J. Lomas, *Rep. Brit. Assoc.*, 1907 (Leicester), 1908, p. 516.
- ¹³ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

BOEHMITE

(LEPIDOCROCITE FAMILY)

Chem. Comp. $4[\text{AlO} \cdot \text{OH}]$, the γ phase.

System. Orthorhombic; dipyrarnidal.

Habit. Lenticular, tabulated. Frequently in pisolitic aggregates.

Structure. Microscopic crystalline, often basal plates (001).

Cleavage. Good, prismatic.

Fracture. Uneven.

Hardness. —

Spec. Grav. 3.1.

Lustre. Vitreous, resinous or dull.

Colour. White, brown.

Mag. Prop. Non-magnetic.

Elect. Prop. —

Opt. Prop. R.I. high, 1.64 (mean). Optical properties uncertain, but probably biaxial, negative (Dana). $Y = c$, $Z = b$.

Characters in Sediments. Usually associated in aggregates with gibbsite (p. 110) from which it may have been formed by dehydration of that species.

Occurrence. In the lithomarges and laterites of Antrim, N. Ireland¹.

Possible Sources of Derivation. Gibbsite, bauxite, laterite.

Reference

¹ V. A. Eyles, F. A. Bannister, G. W. Brindley and J. Goodyear, *Mem. Geol. Surv., N. Ireland*, 1952, p. 39.

General Reference

J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, p. 645 and refs. cited (p. 646).

BRONZITE

(VARIETY OF ENSTATITE. *q.v.* p. 101)

BROOKITE

[Pl. 12, between pp. 64-65]

Chem. Comp. TiO_2 .

System. Orthorhombic.

Habit. Prismatic, tabular, $\parallel (100)$, $\parallel (001)$ or pyramidal. Often striated \parallel principal axis.

Structure. Crystalline.

Cleavage. Poor $\parallel (110)$ and (001) .

Fracture. Subconchoidal, irregular.

Hardness. 5.5-6.

Spec. Grav. 3.87-4.08.

Lustre. Resinous, vitreous, submetallic.

Colour. Shades of brown and yellow. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 2.583$, $\beta = 2.586$, $\gamma = 2.741$. Birefringence very strong, $\gamma - \alpha = 0.158$. Optically biaxial, positive. $Bxa = Z \parallel a$, $\perp (100)$. Optical properties are anomalous; optic axial plane $\parallel (001)$ for red and yellow light and $\parallel (010)$ for green and blue light, *i.e.* $Xr \parallel b$, or $Xbl \parallel c$. For intermediate colour (yellow-green) brookite is uniaxial and isotropic. Optic axial angle varies: for red light $2E = 55^\circ$, for yellow $2V = 30^\circ$, for green $2E = 34^\circ$, for yellow-green $2E = 0^\circ$. $Z > Y > X$, or $Y > Z > X$. Non-pleochroic as a rule, but (001) grains are pleochroic. Many crystals fail to extinguish in any position; some show straight extinction \parallel principal striæ or prism-edge. Dispersion very strong. For a full and illustrated discussion on the optical properties of detrital brookite, see reference¹¹, p. 66, and Note, p. 65.

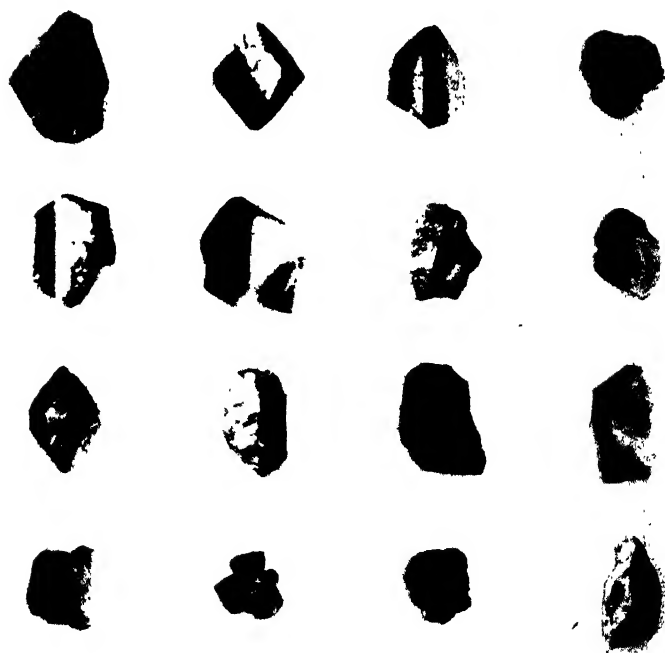
Characters in Sediments. Detrital brookite is a somewhat elusive species. Normally occurs as dusky brown or yellow grains, tabular $\parallel (100)$, while (110) and (010) types are observed. Noteworthy absence

[cont. on p. 66.]



A. ARAGONITE

Shell fragments, Shore Sand, Aberdeenshire [x 22]



B. ARSENOPYRITE.

Alluvials, Bear Hill, New South Wales
[Top & trans light, x 40]



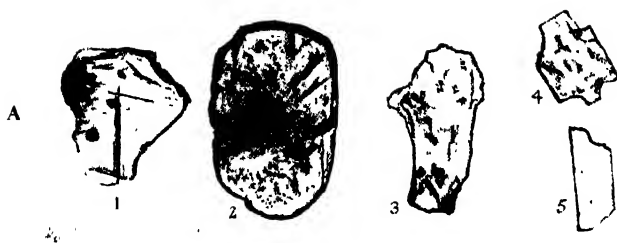
A. B. AUGHIL.

- A 1, 2 Recent Sands, Rosslare, Co. Wexford [x 70]
 3 Recent Sands, Cape Verde Is. [x 70]
 4 Blown Sands, Newgate, Pembrokeshire. [x 70]
 B River Sand, Tyrol [x 70]



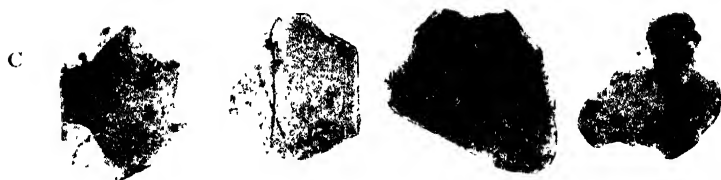
C. AXINIT.

- 1-3 Shire Sand, near Carrick Du, St. Ives, Cornwall [x 40]

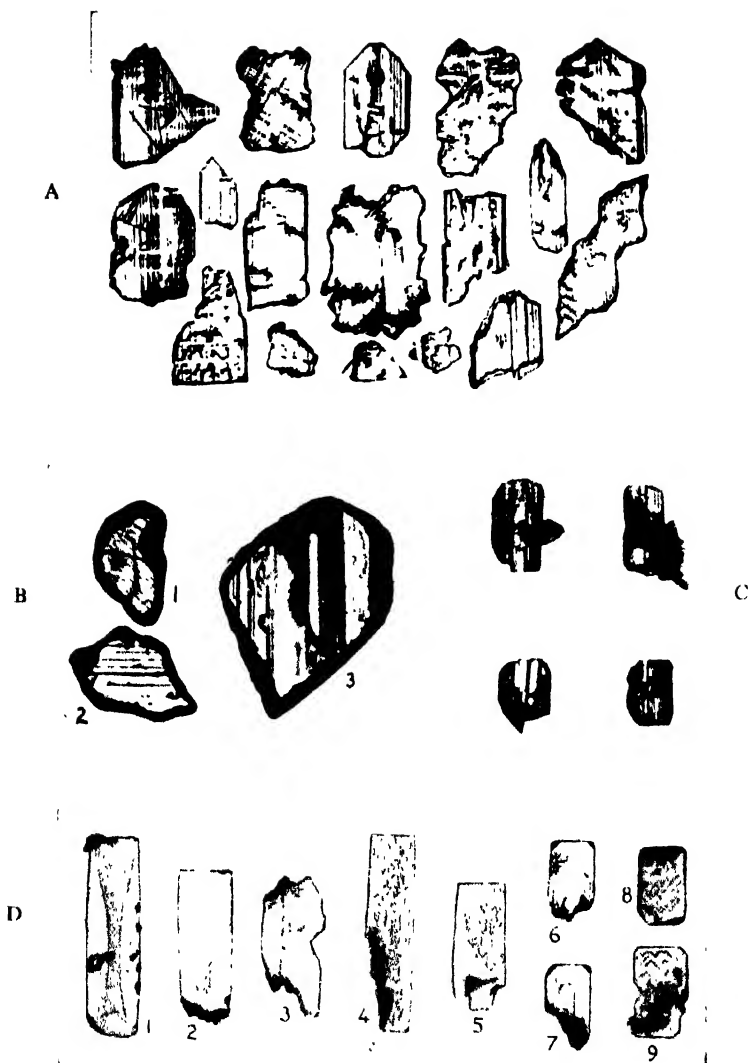


A, B BARIUM

- A 1, 2 Shore Sand, Co. Cork, I.F.S. [x 35]
 3, 5 Keuper Sand, Alderley Edge, Cheshire [x 35]
 B River Sand, R. Eden, Cumberland [x 22]



C BARIUM



A-D BROOKITE.

- Shore Sand, Dinard, Brittany [x 23]
 A. Typical Crystals and fragments from Dartmoor (From brush-drawings by A. Brammell) Grade-size 0.2-1.4 mm.
 B. 1-2. Worn detrital grains, Trias, Yorkshire [x 210]
 3. Worn detrital grain, Glacial Sand, Yorkshire. [x 210]
 C. Middle Jurassic, Yorkshire (Authigenic) [x 66]
 D. 1-7 Middle Jurassic, Yorkshire (Authigenic, tabular on 001) [x 150]
 8, 9 Lower Carboniferous Northumberland (Authigenic, tabular on 001) [x 150]
 (Note. D 1-9. Optically anomalous grains from wash drawings by F. Smithson)

NOTE ON THE INTERFERENCE FIGURE OF BROOKITE (DARTMOOR). (Quoted from A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 33.)

- (a) Under the best conditions, the figure shows well-defined compound lemniscates approximating to arcs. In the "straight" position it has the aspect of *Fig. 1*, changing, on rotation through 45° , to *Fig. 2* and *Fig. 3* in succession.

In *Fig. 1* the N.-S. central bar is the more sharply defined and is flanked by reddish tints near the poles. The E.-W. bar is somewhat dispersed, the polar tints being dominantly greenish. The arc-like colour-bands are compounded of green and red, shading into yellow and orange in the inter-spaces. In each band, the red arc is more convex than the green, and the two overlap; the overlap segments are strikingly darker than the rest of the band.

- (b) Under less favourable conditions, the colour-bands shown in *Figs. 1*, *2* and *3* become indistinct or indiscernible: the colour-patterning shows an area spread of tints (*Fig. 1a*). On rotation through 45° four broad isogyral colour-bands evolve (*Figs. 2a* and *3a*)—in place of the two sharply defined "black" isogyres shown by a normal biaxial figure. In each of the phases *1a*, *2a* and *3a*, reddish tints dominate one pair of opposed quadrants; greenish tints dominate the other pair.

- (c) In the "straight" position the figure shows the usual dark (neutral grey) cross. On the slightest rotation from this position each of the four arms of the cross becomes reddish on one side, greenish on the other (*Figs. 4a* and *4b*). If rotation be continued through 45° , the green and red tints spread centrosymmetrically, in the manner shown in *Figs. 2a* and *3a*.

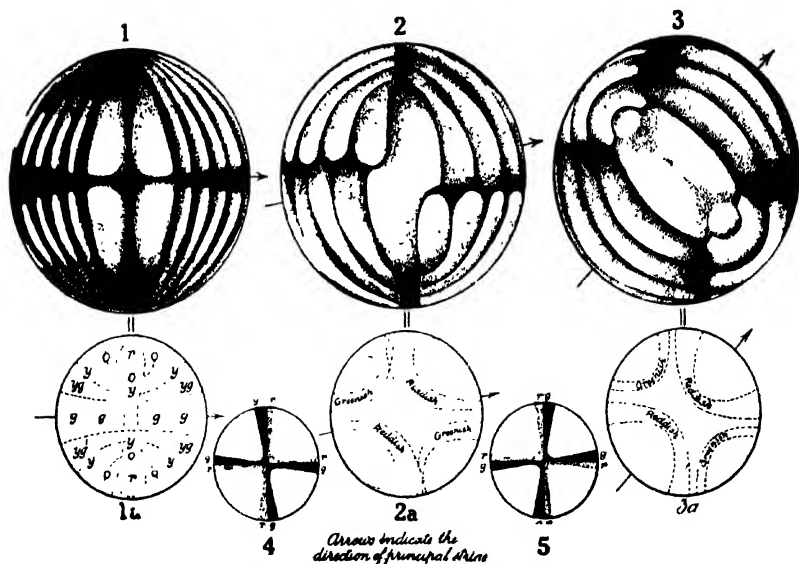


FIG. 37. Interference Figure of Brookite (Dartmoor).—A. Brammall.

of extinction; interference colour change on rotation. Striae || principal axis are common, also noted by A. Brammall || b-axis. Inclusions are commonly detected, these being 'aggregates and stringers of opaque dust', also in the Dartmoor types, rutile, tourmaline, rarely topaz and globular isotropic bodies.

Occurrence. In the Cambrian Quartzites of Shankill, Ireland¹; in the Bunter Pebble Bed of the West of England²; in the New Red Sandstone of the West of England³; in the Jurassic sandstones of Eskdale, Yorkshire⁴; in the Cleveland Ironstone⁵; in the Upper Lias—Lower Inferior Oolite sands of the West of England⁶; in the Greensand of the Haldon Hills, Devonshire⁷; in the Oligocene beds of the Bovey Basin, Devonshire⁸; in the Pliocene deposits of West Cornwall⁹; in the later Tertiary deposits (Red Crag, Chillesford Beds, etc.) of East England¹⁰; in Dartmoor detritals¹¹.

Later Records. In Millstone Grit, Ellingstring, Yorkshire and Garth, Denbighshire¹²; in Liassic Ironstones, Cleveland, Yorkshire¹³; in Middle Jurassic, Howard Hills and Scarborough, Yorkshire¹⁴; in Lower Greensand, E. Kent¹⁵.

Possible Sources of Derivation. Acid igneous and crystalline metamorphic rocks; from the pneumatolysis and tourmalinization of titaniferous biotite. See A. Brammall, *op. cit.* p. 47, also this volume, under ilmenite, p. 128. When abundant probably authigenic.

REMARKS.—Students of the titanium minerals in sediments owe much to A. Brammall and H. F. Harwood for their exhaustive studies of these species, particularly brookite, which has always presented certain difficulties in unequivocal diagnosis. In the paper on 'Dartmoor Detritals'¹¹, the former author gives much information applicable to the identification of brookite under all conditions, together with some good illustrations of the Dartmoor types and their curious interference figures, the latter here reproduced in Fig. 37, p. 65.

References

- ¹ J. P. O'Reilly, *Sci. Proc. Roy. Dublin Soc.*, **8**, 1898, p. 732.
- ² H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 625, Pl. 32, Fig. 6.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 238.
- ⁴ R. H. Rastall, *Proc. Yorks. Geol. Soc.*, **22**, 1932, p. 93.
- ⁵ J. E. Stead, *Proc. Cleveland Inst. Eng., Middlesbrough*, 1910, p. 75.
- ⁶ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 257.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 210.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ⁹ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, pp. 362, 364.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 340.
- ¹¹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 31.
- ¹² F. Smithson, *Geol. Mag.*, **91**, 1954, p. 180.
- ¹³ T. H. Whitehead and ors., *Mem. Geol. Surv.*, 1952, p. 27.
- ¹⁴ F. Smithson, *Geol. Mag.*, **91**, 1954, p. 180.
- ¹⁵ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.

General References

- F. C. Phillips, Crystals of Brookite Tabular Parallel to the Basal Plane, *Miner. Mag.*, **23**, 1932, p. 126.

R. H. Rastall, *Geol. Mag.*, **75**, 1938, p. 433.

F. Smithson, *The Middle Jurassic Rocks of Yorkshire: A Petrological and Palaeogeographical Study*, *Quart. Journ. Geol. Soc.*, **98**, 1942, p. 27 (p. 32 Brookite).

BYTOWNITE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. $8[(\text{NaSi}, \text{CaAl}) \text{AlSi}_2\text{O}_6]$.

System. Triclinic.

Habit. Seldom well defined as crystals. Usually massive, prominent twinning on (010) with broad lamellæ.

Structure. Massive, compact, microcrystalline.

Cleavage. Perfect \parallel (100), distinct \parallel (010).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 2.73.

Lustre. Vitreous, pearly.

Colour. Colourless, grey, green, white.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha \approx 1.566$, $\beta \approx 1.572$, $\gamma \approx 1.576$. Birefringence moderate, $\gamma - \alpha \approx 0.010$. Optically biaxial, negative. $Bxa \approx X$ inclined about 30° to (001) and 35° to (010). A. N. Winchell gives extinction angles $\perp X - 58^\circ$, $\perp Z - 49^\circ$, $\parallel (001) - 18^\circ$, $\parallel (010) - 31^\circ$, max. $\perp (010) + 42^\circ$. $2V \approx 82^\circ$. Dispersion $\rho > \nu$.

Characters in Sediments. Bytownite is probably the rarest of the plagioclase feldspar group in basic igneous rocks and consequently its occurrence in detrital form is correspondingly restricted. Where suspected, its diagnosis depends on presence of twin lamellæ, identification of crystal face(s) presented by the grain or flake(s) and measurement of R.I. and extinction angles.

Occurrence. In the soils of Kediri, Java¹.

Possible Sources of Derivation. Basic igneous plutonic and volcanic rocks. More rarely anorthosite (gabbro practically free from pyroxene, composed chiefly of bytownite).

Reference

¹ G. A. Neeb, *Overdruk uit de Handelingen v/h. 74^e Ned. Ind. Natuurwetenschappelijk Congres*, 1936, p. 695.

CALCITE

[Pl. 13A-C, between pp. 80-81]

Chem. Comp. CaCO_3 .

System. Trigonal.

Habit. Highly varied and frequently complex. Commonly prismatic, rhombohedral, scalenohedral or twinned on (0001) or (00 $\bar{1}$ 2).

Structure. Crystalline or massive.

Cleavage. Perfect \parallel unit rhombohedron (10 $\bar{1}$ 1). Good parting \parallel (01 $\bar{1}$ 2) in twin crystals, more rarely \parallel (11 $\bar{2}$ 0).

Fracture. Irregular, but rare.

Hardness. Varies with composition, but usually about 3.

Spec. Grav. 2.71–2.72.

Lustre. Vitreous, pearly.

Colour. Colourless, white or pale shades of yellow, red or brown, due to impurity. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low for ϵ , high for ω . $\omega = 1.658$, $\epsilon = 1.486$. Birefringence very strong, $\omega - \epsilon = 0.172$. Optically uniaxial, negative. (10 $\bar{1}$ 1) cleavage plates show partial interference figure; symmetrical extinction.

Characters in Sediments. Usually occurs as highly irregular grains, slightly rounded. Twin striæ || the major diagonals of the cleavage flakes (10 $\bar{1}$ 1) often observed. Diagnosed chiefly by lamellar twinning, 'twinkling' effect noted on rotation of polarizer, strong birefringence, uniaxial negative figure of distinctive type.

Occurrence. In the Old Red Sandstone of the West Midlands¹; in the Permo-Triassic rocks of the Midlands²; in the Lower Greensand of Kent and Surrey³; in the Upper Greensand of Dorset⁴; in Oligocene 'glass' sand, Fontainebleau, Paris⁵; in the dune sands of South Wales⁶; in surface deposits of S.E. Devonshire⁷; in shore sand Kynance, Cornwall⁸.

Later Records. In Liassic Ironstones, Cleveland, Yorkshire¹⁰; in Beach Sand, Carbis Bay, Cornwall¹¹.

Possible Sources of Derivation. Chiefly from sedimentary rock masses, either as a primary or secondary constituent. Also from decomposition of lime-silicate minerals in igneous rocks. Recrystallized from shell-fragments⁹.

REMARKS.—Calcite very rarely occurs as simple rhombohedra in sediments; such forms are generally ascribable to dolomite. Like dolomite and magnesite, it differs from the other species of the calcite group (e.g. siderite, smithsonite) in having one R.I. lower than that of Canada balsam. Where diagnosis is doubtful, chemical tests must be made, especially for distinction from dolomite. The principal tests are:—(1) Vigorous effervescence with cold HCl; dolomite effervesces slowly, if at all. Both minerals react readily to warm HCl. (2) With ferric chloride gives reddish-brown deposit of ferric hydroxide; dolomite only affected after prolonged treatment. (3) *Lemberg's Test*: 60 parts H₂O, 4 parts Al₂Cl₆ and 6 of logwood chips (*Haematoxylon campechianum*) boiled together for 25 minutes; when cool treat mineral with this solution: calcite takes the stain after 5 to 10-minutes, dolomite remains unaltered. For other tests, see A. Holmes, *Petrographic Methods*, (Murby, London), 1921, ch. vii.

References

¹ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 512.

² W. F. Fleet, *Proc. Geol. Assoc.*, **38**, 1927, p. 6.

³ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, p. 90.

^{4, 5} Author's observations.

- ⁶ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 322.
⁷ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 145.
⁸ Author's observations.
⁹ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 255.
¹⁰ T. H. Whitehead and ors., *Mem. Geol. Surv.*, 1952, p. 24.
¹¹ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

CARPHOLITE

Chem. Comp. $\text{MnAl}_2\text{Si}_2\text{O}_8(\text{OH})_4$.

System. Orthorhombic.

Habit. Fibrous; radiated and stellated tufts.

Structure. Crystalline, acicular.

Cleavage. Perfect $\parallel (010)$.

Fracture. Irregular; brittle.

Hardness. 5-5.5.

Spec. Grav. 2.9.

Lustre. Vitreous, silky or glistening.

Colour. Straw to wax yellow.

Mag. Prop. —

Elect. Prop. —

Opt. Prop. R.I. high, $\alpha = 1.611$, $\beta = 1.628$, $\gamma = 1.630$. Birefringence moderate, $\gamma - \alpha = 0.019$. Optically biaxial, negative. Optic axial plane $\parallel (100)$. $2V = 60^\circ \pm$. $Z = c$, $X = b$. Elongation $+$. $Bxa \perp (010)$; $Bxo \wedge c = 3^\circ - 5^\circ$. $\rho > \nu$, rather strong. Pleochroism $X = Y =$ pale yellow, $Z =$ colourless. Maximum absorption \perp to elongation.

Characters in Sediments. A little known and rare mineral as detrital, but see Remarks below.

Occurrence. In quartz pebbles, near Meuville, Ardennes¹; in greywacke, Noil Noni, Miomaffo region, Timor, Indonesia².

Possible Sources of Derivation. Quartz; greywacke; metalliferous veins (tin).

REMARKS.—‘The most characteristic optic feature of this mineral is its tourmaline-like pleochroism with maximum absorption perpendicular to the elongation, but in yellow hues: elongation parallel to c and positive, $Z = c$ (colourless), $Y = a$ and $x = b$ (light yellow). Cleavage (010) and (110), biaxial and negative with $2V$ about 60° , refringence about 1.63, birefringence about 0.02, parallel extinction’³.

References

- ¹ J. D. and E. S. Dana, *System of Mineralogy*, 6th ed., (Kegan Paul, Trench, Trübner, London), 1892, p. 549.
^{2,3} Personal communication from W. P. de Roever to the author (1958).

CASSITERITE

[Pl. 13D-F, *between pp.* 80-81]*Chem. Comp.* SnO_2 .*System.* Tetragonal.*Habit.* Commonly euhedral. Short bipyramidal, prismatic or twinned on (101).*Structure.* Crystalline, massive, granular.*Cleavage.* Imperfect \parallel (100), poor \parallel (111), trace \parallel (110).*Fracture.* Subconchoidal, uneven.*Hardness.* 6-7.*Spec. Grav.* 6.8-7.1.*Lustre.* Adamantine, submetallic or dull.*Colour.* Brown, black, reddish-brown, more rarely pale yellow or greyish-white. Translucent to opaque.*Mag. Prop.* Usually non-magnetic, but magnetic varieties known.*Elect. Prop.* Moderate conductor.*Opt. Prop.* R.I. very high, $\omega = 1.997$, $\epsilon = 2.093$. Birefringence strong, $\epsilon - \omega = 0.096$. Optically uniaxial, positive. Length slow. Straight extinction. Interference figure often 'splits' into pseudo-biaxial type in certain varieties: small axial angle. Interference colours frequently masked by natural colour. Rarely pleochroic: ω - brown, yellow, red, pink; ϵ - grey-green, yellow, red.*Characters in Sediments.* Commonly occurs as prismatic and pyramidal grains, or as irregular rolled crystals, either opaque with marked adamantine lustre or of composite colour in which brown and red of different shades predominate. The colour is often distributed irregularly in the grain, giving a blotchy appearance; or some individuals may present small translucent patches in an otherwise opaque mass. Detrital, like alluvial, cassiterite is extremely variable in character, especially as regards its pleochroism, which in examples from some localities is consistently developed. Inclusions in translucent varieties are common and are nearly always iron oxide. Zoning is frequent and some very beautiful examples of colour-band patterning are met with. Knee-shaped twins, characteristic of many alluvial occurrences, are rare as detrital grains. Well marked fluting or finer striæ \parallel principal axis are commonly noted in prismatic grains, while striæ \parallel pyramidal faces occur (Dartmoor).*Occurrence.* In the New Red Sandstone of the West of England¹; in the Bunter Pebble Bed of the West of England²; in the Greensand, Eocene, Oligocene and Pliocene deposits of the West of England³; in the Pliocene deposits of Cornwall⁴; in the dune sands of South Wales⁵; in Dartmoor detritals⁶; in Clay-with-Flints, Walton Heath, Surrey⁷; in the shore sand of St. Ives Bay, Cornwall⁸.*Later Records.* In Beach Sand, Carbis Bay, Cornwall⁹; in Residual deposits, Muntok district, N.W. Banka, Indonesia¹⁰.*Possible Sources of Derivation.* From veins, pegmatites, etc., associated with granite rocks; from metalliferous lodes. Rarely a minor accessory species in granite itself.

REMARKS.—Cassiterite as a constituent of detrital sediments is probably more common than existing records suggest, but is liable to be confused with rutile, hypersthene, titanite or other 'dusky' brown minerals. Microscopical diagnosis is by no means always unequivocal and the simple zinc and HCl test should always be resorted to wherever possible. This consists of the use of a metallic zinc bath in which the supposed cassiterite grains are placed, then covered with dilute HCl; the nascent hydrogen evolved results in an aluminium-grey coating to the tinstone, which can easily be detected under the microscope and is positive.

References

- ¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 231.
- ² H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 623.
- ³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ⁴ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 359, 364.
- ⁵ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 321.
- ⁶ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 36 and Pl. 2.
- ⁷ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.
- ⁸ T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 120.
- ⁹ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.
- ¹⁰ J. W. A. Bodenhause, *Proc. Koninkl. Nederl. Akademie van Wetenschappen—Amsterdam*, Series B, **57**, 1954, p. 322.

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 C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 362 (for full description of alluvial occurrences).

CELESTITE

Chem. Comp. SrSO_4 .

System. Orthorhombic.

Habit. Tabular \parallel (001); prismatic; less commonly pyramidal.

Structure. Crystalline, fibrous, radiating.

Cleavage. Perfect \parallel (001), good \parallel (110), imperfect \parallel (010). Prismatic cleavage 75° .

Fracture. Irregular, distinct.

Hardness. 3-3.5.

Spec. Grav. 3.95-3.97.

Lustre. Vitreous.

Colour. Colourless, white, pale blue, rarely pink.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.622$, $\beta = 1.624$, $\gamma = 1.631$. Birefringence weak, $\gamma - \alpha = 0.009$. Optically biaxial, positive. $Bxa = Z \perp (100)$. Optic axial plane \parallel (010). $X \parallel c$, $Z \parallel a$. Straight extinction \parallel prism-edge. $2V = 51^\circ$. $2E = 80^\circ$. Dispersion, $\rho < \nu$. Normally non-pleochroic. Blue varieties faintly pleochroic, maximum absorption $\parallel X$.

Characters in Sediments. Celestite, like barite and anhydrite, is almost invariably authigenic, associated with limestone, certain sandstones in

which it occurs as a cementing medium, marls, gypsum and rock-salt. Consequently when isolated as detached flakes it tends to be of fantastic shape, *i.e.* the shape of the original interstice which it filled. There is little available on microscopical evidence *alone* to determine definitely this species, which is liable to confusion with related sulphates and with other colourless minerals. Since when it does occur it is usually prolific, little difficulty is experienced in applying the customary flame-test (crimson) or spectroscopic methods of discrimination. Insoluble in HCl.

Occurrence. In the New Red Sandstone of the West of England¹; in the Triassic gypseous deposits and dolomites near Jena, Germany²; in Triassic sandstones and marls of Yate, Gloucestershire³.

Possible Sources of Derivation. From cementing (authigenic) media in calcareous and arenaceous rocks; from geodes and secondary masses in marls; from veins and metalliferous bodies.

References

¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 234.

² E. Kalkowsky, *Zeitschr. deutsch geol. Gesellsch.*, **73**, 1922, p. 1.

³ Well-known locality.

CEYLONITE (PLEONASTE)

(SPINEL GROUP)

[Pl. 14A, between pp. 80 81]

Chem. Comp. (Mg, Fe)O . Al₂O₃.

System. Isometric.

Habit. Octahedral, sometimes with dodecahedral development. Occasional twinning on (111).

Structure. Crystalline.

Cleavage. Imperfect || (111).

Fracture. Conchoidal.

Hardness. 8.

Spec. Grav. 3.84.

Lustre. Vitreous; splendent to dull.

Colour. Green, blue-green.

Mag. Prop. Weakly magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, 1.75–1.79 (*A. N. Winchell*), varying with composition and depth of colour. Isotropic.

Characters in Sediments. Usually exhibits some degree of rounding, but the simple octahedral habit is very characteristic and is, in fact, one of the chief diagnostic properties of this mineral in detrital sediments. It is sometimes highly fractured when it may resemble green garnet, a mineral of similar refractive index; green garnet (*vars.* Uvarovite, p. 199, Andradite, p. 41), often exhibits anomalous polarization colours, very rare with ceylonite. This mineral seldom has inclusions; green garnet is liable to show them.

Occurrence. Possibly in the Lower Keuper Sandstone of the English Midlands¹; in the Northampton Ironstone²; rarely in the Sands of

the Upper Lias—Inferior Oolite of the West of England²; in the Spilsby Sandstone (Lower Cretaceous)⁴; in the Thanet Beds of the London Basin⁵; in the Bagshot Beds of Essex⁶; in the Norwich Crag (newer Pliocene) of the East of England⁷; in the Lenham (Pliocene) Beds of Sanderstead, Surrey⁸; occasionally in the shore sands of East England and Brittany⁹; in Dartmoor detritals¹⁰.

Later Records. In Lower Greensand, W. Weald¹¹.

Possible Sources of Derivation. Basic and ultrabasic igneous rocks; metamorphosed limestone, dolomite and argillaceous rocks; aureole and xenolithic hornfels containing corundum, cordierite, etc.

REMARKS.—An infrequent species, though it seems to be a constant constituent of the Lenham Beds; probably often confused with garnet and possibly members of the chlorite group; see also under Spinel (p. 182) for possible method of distinction from garnet.

References

- ¹ W. F. Fleet, *Geol. Mag.*, **62**, 1925, p. 124.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 375.
- ³ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 257.
- ⁴ F. T. Ingham, *Proc. Geol. Assoc.*, **40**, 1929, p. 1.
- ⁵ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1915, table IV.
- ⁶ S. W. Wooldridge, *Proc. Geol. Assoc.*, **35**, 1924, p. 377.
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 338.
- ⁸ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, **37**, 1926, p. 99.
- ⁹ Observations of F. T. Ingham and the author.
- ¹⁰ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 47.
- ¹¹ G. V. Wood, *Proc., Geol. Assoc.*, **67**, 1957, p. 127.

General Reference

- P. G. H. Boswell, The Rarer Detrital Minerals of British Sedimentary Rocks, *Trans. Geol. Soc. Glasgow*, **18**, 1926–27, p. 135.

CHALCEDONY

[Pl. 14B, C, between pp. 80–81]

Chem. Comp. SiO₂.

System. Doubtful.

Habit. Botryoidal, massive.

Structure. Microcrystalline, fibrous.

Cleavage. None.

Fracture. Conchoidal, splintery.

Hardness. 6.

Spec. Grav. 2.55–2.63.

Lustre. Waxy, resinous.

Colour. White, pale blue, yellow, brown. (See varieties below.)

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $n = 1.537$. Birefringence weak, $\omega - \epsilon = 0.007$ (A. N. Winchell). Optical characters not known definitely. Fibres believed to be biaxial, positive and give straight extinction. Elongated

along *bxo*, i.e. negative (*H. A. Miers*). In some cases fibres have positive elongation $\parallel \gamma$ (*A. N. Winchell*). Other varieties exhibit aggregate polarization.

Characters in Sediments. Grains usually angular, white or pale blue, sometimes with distinct layering or banding, seen to advantage with vertical illumination. Diagnosed by its lower S.G. than quartz, lower R.I. than Canada balsam, its fibrous character seen under high power magnification and anomalous optical properties.

Occurrence. For *Chalcedony*: in the Wenlock Limestone, England¹; in the Silurian Sediments near Melbourne, Australia²; in the Franciscan limestone (Trias) of California³; in the Upper Lias-Inferior Oolite of the West of England⁴; in the Bargate Stone (Lower Greensand) near Guildford, Surrey⁵; in certain horizons of British Chalk⁶; in the Eocene Bed deposits of Utah and Colorado, U.S.A.⁷; in the river and sand dunes of Italian Somaliland⁸; in deposits at the bottom of Lake Como, Italy⁹; in the Mallee soil of Western Australia¹⁰. For *Chert* and *Flint*: in the Upper Lias-Inferior Oolite Sands of the West of England¹¹; in the Cretaceous and Tertiary rocks of the West of England¹²; in the Cretaceous rocks of the Croydon Regional Survey Area, Surrey¹³; in the Dune Sands of South Wales¹⁴.

Later Records. In Bargate Beds, Churt, Surrey¹⁵.

Possible Sources of Derivation. Geodes, cavities, veins in decomposed igneous rocks. Inorganic: siliceous deposits from aqueous solution.

REMARKS.—Chalcedony is a highly variable mineral to which, when coloured, various names have been given, as also to mixtures with *Opal* (p. 154) and *Quartz* (p. 171). *Agate* is banded and variegated chalcedony. *Bloodstone* is *Plasma* (q.v. below) spotted with *Jasper*. *Cornelian* is the red variety. *Chrysoprase* is green chalcedony, colour due to nickel. *Heliotrope* is the same as *Bloodstone*. *Jasper* is a mixture of quartz with clay, limonite, iron oxide, etc. *Moss Agate* is a variety of *Agate*. *Onyx* is a variety of *Agate*. *Plasma* is pale green chalcedony. *Prase* is green quartz in which chlorite is the pigment. *Sard* is brown-red, horn-like chalcedony.

Closely allied are *Chert*, *Flint* and *Hornstone*, a flinty variety of chalcedony often associated with volcanic rocks. Chert grains frequently occur as conspicuous constituents of detrital sediments; such grains may preserve traces of organic structure or they may be associated with pellets of pyrite. They frequently exhibit aggregate polarization and are far more varied in character than pure chalcedony. Average particles are usually optically inert and are diagnosed chiefly by their appearance, by reflected light, also by fracture. For fuller description of both chert and flint, see Chapter II, p. 256.

References

- ¹ E. Wethered, *Quart. Journ. Geol. Soc.*, **49**, 1893, p. 236.
- ² W. G. Langford, *Proc. Roy. Soc. Victoria*, **29**, 1916, p. 40.
- ³ E. F. Davis, *Univ. California Publ., Bull. Dept. Geol. Sci.*, **11**, 1918, p. 1.
- ⁴ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 252.
- ⁵ W. F. Hume, in F. Chapman, *Quart. Journ. Geol. Soc.*, **50**, 1894, p. 677.
- ⁶ I. S. Double, *Journ. Roy. Micros. Soc.*, **47**, 1927, p. 226.

- ⁷ W. H. Bradley, *U.S. Geol. Surv., Prof. Paper* 158-A, 1929.
⁸ E. Artini, *Atti Soc. ital. Sci. nat.*, **54**, 1915, p. 137.
⁹ E. Artini, *Rend. R. Ist. lombardo*, **36**, 1903, p. 596.
¹⁰ D. A. Carroll, *Journ. Roy. Soc. West Australia*, **20**, 1933-4, p. 100.
¹¹ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 252.
¹² P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
¹³ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 87.
¹⁴ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 325.
¹⁵ J. A. Richardson, *Proc. Geol. Assoc.*, **58**, 1947, p. 161.

General References

- C. R. Pelto, A Study of Chalcedony, *Amer. Journ. Sci.*, **254**, 1956, p. 32.
 F. Smithson, Silica Particles in Some British Soils, *Journ. Soil Sci.*, **7**, 1956, p. 122.

CHALCOPYRITE

(COPPER PYRITES)

Chem. Comp. CuFeS_2 .

System. Tetragonal, scalenohedral.

Habit. Tetrahedral, sphenoidal; often twinned and striated.

Structure. Crystalline, botryoidal or reniform.

Cleavage. Distinct \perp (011).

Fracture. Uneven.

Hardness. 3.5-4.

Spec. Grav. 4.1-4.3.

Lustre. Metallic.

Colour. Brass yellow, tarnished, iridescent (Peacock Ore).

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. Opaque. In polished section weakly anisotropic (Dana).

Characters in Sediments. Brass yellow or iridescent, irregular, shaped grains showing traces of crystalline structure and frequently striae, if crystal faces are preserved.

Occurrence. In Beach Sand, Carbis Bay, Cornwall¹.

Possible Sources of Derivation. Ore bodies and mineral veins in contact-metamorphic zones.

REMARKS.—In Cornwall frequently associated with cassiterite (p. 70) and pyrite (p. 167).

Reference

- ¹ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General Reference

- J. D. and E. S. Dana and ors., *System of Mineralogy*, (Wiley, New York, Chapman & Hall, London) **1**, 7th. ed., 1955, p. 219.

CHAMOSITE*

Chem. Comp. $[(\text{Fe}, \text{Mg})_{12}(\text{Al}, \text{Fe})_{12}(\text{Si}, \text{Al})_{16}\text{O}_{40}(\text{OH})_{32}]$.

System. Monoclinic.

Habit. Oolitic; platy like mica; or as crystalline and/or earthy matrix.

* See Ch. III, p. 315.

Structure. Crystalline, microcrystalline.

Cleavage. Strong basal; also prismatic.

Fracture. Irregular; radial in oolites if prismatic cleavage present.

Hardness. 3.

Spec. Grav. 3-3.5.

Lustre. Vitreous.

Colour. Green; brown due to oxidation or intimate association with limonite, siderite, etc.

Mag. Prop. Weakly magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, 1.62-1.66. Birefringence weak to moderate (0.010-0.012). Sometimes practically isotropic. Optically biaxial; sometimes pseudo-uniaxial; negative. Optic axial angle small. Weakly pleochroic, X = yellow or colourless; Y = Z = pale green. 'Pleochroism is well marked, green or yellow green for rays vibrating at right angles to the cleavage, deep olive green for rays vibrating parallel with it'. (J. H. Taylor, Ref. ¹ below, p. 17.)

Characters in Sediments. Most often seen as oolites in sedimentary iron ores, but otherwise to be anticipated in the form of flakes resembling the micas. There is a slight tendency to crystal elongation normal to basal cleavage which may prove diagnostic in difficult cases. Chamosite also characterizes green mudstones in similar environments, when it has more the appearance of an amorphous than a crystalline constituent.

Occurrence. In the Northampton Sand (Ironstone), Northamptonshire and Lincolnshire¹; in Liassic Ironstones, Cleveland, Yorkshire²; in Laterite deposits, Co. Antrim³.

Possible Sources of Derivation. Much may be of secondary origin, e.g. in glauconitic laterites. Chemically precipitated chamosite muds.

REMARKS.—Chamosite in sediments, especially in bedded iron ores, is a rock-forming mineral of considerable importance and versatility in occurrence. Both crystallographically and optically it behaves rather as a somewhat erratic mixture of a ferrous-aluminous silicate, plus intimately associated, more specific iron ore components, rather than as a uniform, individual mineral species. Its relationships with the chlorite and kaolinite groups have been fully discussed in the literature (see below), but despite a wealth of description, it is still a somewhat enigmatic substance if the published diagnoses are always correct.

References

- ¹ J. H. Taylor, *Mem. Geol. Surv.*, 1949 (excellent coloured illustrations).
- ² T. H. Whitehead and ors., *Mem. Geol. Surv.*, 1952, p. 17.
- ³ V. S. Eyles, F. A. Bannister, G. W. Brindley and J. Goodyear, *Mem. Geol. Surv.*, 1952, p. 47.

General References

- A. F. Hallimond, *Spec. Rep. Min. Res. Gt. Brit.*, **29**, 1925, p. 26.
- A. F. Hallimond, On the Relation of Chamosite and Daphnite to the Chlorite Group, *Miner. Mag.*, **25**, 1939, p. 441.
- F. A. Bannister and W. F. Whittard, A Magnesian Chamosite from the

Wenlock, Limestone of Wickwar, Gloucestershire, *Miner. Mag.*, 27, 1945, p. 99.

G. W. Brindley and ors., *X-ray Identification and Crystal Structures of Clay Minerals* (Miner. Soc., London), 1951, p. 64.

CHERT

(See Chalcedony, p. 73)

CHIASTOLITE

(VARIETY OF ANDALUSITE, p. 39)

[Pl. 14D-F, between pp. 80-81]

Chief mineralogical properties as for Andalusite.

Characters in Sediments. Where graphitic or carbonaceous inclusions are concentrated within the mineral grain so as to exhibit a tessellated or geometrical design, *e.g.* a black cross, the variety 'chiastolite' is diagnosed. There is, however, some difference of opinion among petrographers as to what should and what should not be called 'chiastolite', since every gradation is met with in detrital sediments from colourless andalusite with a few irregularly scattered carbonaceous inclusions to those grains in which the black cross is definite. I. S. Double states, 'The quantity and the mode of arrangement of the black inclusions is very variable. When part or all of the black cross associated with varietal characters of chiastolite has been seen, that mineral is recorded'⁴. Although this only applies to a specific instance (late Tertiary deposits of the East of England), it is, in the author's opinion, the correct interpretation in all circumstances and where the inclusions are disseminated quite arbitrarily in the grains, these are better recorded as andalusite.

On the whole definite grains of chiastolite seldom show pleochroism so characteristic of many occurrences of andalusite and grains preserving the complete black cross are uncommon. I. S. Double illustrates four types of chiastolite in his paper; P. G. H. Boswell also figures two examples from the Oligocene beds of Devonshire. Detrital chiastolite is more often than not irregular in form, though occasionally the orthorhombic prism is preserved, when the grain exhibits straight extinction.

Occurrence. In the Sands of the Upper Lias—Lower Inferior Oolite of the West of England(?)¹; in the Oligocene Beds of the Bovey Basin, Devonshire²; in the gravels of doubtful age at Riddaford Water, Bovey, Devonshire³; in the Red Crag and Coralline Crag (Pliocene) of the East of England⁴; in the Lenham Beds of Sanderstead, Surrey⁵ and of the Folkestone district⁶; in the matrix of the Pebble Gravel of the Hertfordshire plateau⁷; in the Chalky-Jurassic Boulder Clay of Foxhall Road, Ipswich⁸; in the Basement Clay at Dimlington⁹.

Possible Sources of Derivation. Metamorphosed argillaceous rocks, *e.g.* chiastolite slate.

REMARKS.—F. Smithson states that in sands and soils derived from the Skiddaw slate most of the chiastolite grains tend to rest on a prism

face and show only a dark 'core'. Only a small proportion can be made to stand on (001) and show the cross pattern¹⁰.

References

- ¹ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 258.
- ² P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, pp. 218, 220.
- ³ *Ibid.*, p. 223.
- ⁴ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 337, 339.
- ⁵ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, **37**, 1926, p. 98.
- ⁶ Author's observations.
- ⁷ S. W. Wooldridge and D. M. C. Gill, *Proc. Geol. Assoc.*, **36**, 1925, p. 171.
- ⁸ P. G. H. Boswell and J. Reid Moir, *Journ. Roy. Anthropol. Inst.*, **63**, 1923, p. 229.
- ⁹ H. C. Versey, *Trans. Leeds Geol. Assoc.*, **20**, for 1923-29, 1930, pp. 17, 20.
- ¹⁰ Written communication.

CHLORITE GROUP*

This group includes essentially hydrous silicates of aluminium and magnesium with ferric and ferrous iron, sometimes chromium. The minerals frequently represent alteration products of amphiboles and micas. Some minerals, *e.g.* antigorite (p. 46) often assigned to what was defined as a 'serpentine group' are now recognized as 'end-members' of the chlorite group and this practice is followed herein. The following is a list of the more important species of the chlorite group: only those recorded from sediments are dealt with in this volume, page references being given accordingly:

Amesite.	Diabantite.
Antigorite (p. 46).	Jenkinsite.
Chamosite (p. 75).	Penninite (p. 158).
Clinochlore (p. 84).	Repiddite.
Daphnite.	Thuringite.
Delessite (p. 92).	

From the standpoint of sedimentary petrography it is rare to find references to specific members of the chlorite group in the literature. Usually the word 'chlorite' is recorded for the somewhat nondescript, green or greenish-yellow 'ultra-blue' polarizing grains which, for want of definite optical properties, seldom can be more precisely tied down. The so-called 'chlorite' derived from relaxed basic igneous rocks (more particularly their ferro-magnesian constituents) is poorly individualized as crystal and certainly rare in sediments as either penninite, clinochlore or other species. Thus where any doubt exists, the mineral is better designated as 'chloritic matter' rather than 'chlorite' *per se*, implying considerable variation in composition according to precise nature of parent minerals and destabilizing environment.

For comparison of his examples with detrital species having definite optical properties, the reader is referred to the four principal members of the group, *antigorite*, *clinochlore*, *delessite* and *penninite*, fully treated herein on the pages indicated above.

* See Ch. III, p. 327.

In so far as records of 'chlorite' in sediments may be of value, the following British occurrences may be cited:

Occurrence. In the Cambrian, Devonian, Carboniferous and Permian-Triassic rocks of the English Midlands¹; in the Old Red Sandstone of the West Midlands²; in the New Red Sandstone of the West of England³; in the Upper Lias—Lower Inferior Oolite of the West of England⁴; in the Northampton Ironstone⁵; in the Pliocene sands of West Cornwall⁶; in the later Tertiary deposits of the East of England⁷; in the dune sands of South Wales⁸.

Later Records. In Denbigh Grits; Wenlock Greywackes, Wales⁹; in Downtonian beds, Tenbury, Worcestershire¹⁰; in Lower Greensand, East Kent¹¹.

References

- ¹ W. F. Fleet, *Geol. Mag.*, **62**, 1925, p. 98.
- ² W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 505.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 239.
- ⁴ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 256.
- ⁵ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 382.
- ⁶ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, pp. 357, 362, 365.
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 342.
- ⁸ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 324.
- ⁹ W. A. Cummins, *Geol. Mag.*, **94**, 1957, p. 441.
- ¹⁰ P. S. Walder, *Proc. Geol. Assoc.*, **52**, 1941, p. 247.
- ¹¹ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.

CHLORITOID

(CHLORITOID—OTTRELITE GROUP)

[Pl. 15A, B, *between pp.* 80–81]

Chem. Comp. (Fe, Mg)O . Al₂O₃ . SiO₂ . H₂O.

System. Monoclinic (pseudo-hexagonal) or triclinic.

Habit. Similar to mica: in (001) plates. Sometimes twinned.

Structure. Crystalline; radiating aggregates; curved.

Cleavage. Good \parallel (001), imperfect prismatic \parallel (110); imperfect \parallel (443) inclined about 90° to (001) and about 60° to one another (*J. P. Iddings*).

Parting \parallel (010).

Fracture. Irregular, brittle.

Hardness. 6.5.

Spec. Grav. 3.26–3.57.

Lustre. Pearly.

Colour. Dark green to greenish black, indigo.

Mag. Prop. Weakly magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.720$, $\beta = 1.722$, $\gamma = 1.731$. Birefringence moderate, $\gamma - \alpha = 0.011$. Optically biaxial, positive. Optic axial plane \parallel (010). $Bxa = Z$ inclined at 3°–30° with \perp (001). $X = b$. $2V = 36^\circ$ – 60° . $2E = 64^\circ$ – 118° . Horizontal dispersion, $\rho > \nu$, strong. Pleochroism distinctive: $X =$ shades of green, $Y =$ indigo or blue, $Z =$ yellow or yellowish-green.

Characters in Sediments. Detrital chloritoid is not a common mineral, but it has been definitely determined in a few instances in British sediments (see below). P. G. H. Boswell has described the characters of chloritoid in some detail: '... as scaly flakes ... or wisps ... often consisting of several flakes partly superposed. A second cleavage at about 90 degrees to the almost perfect basal cleavage is sometimes seen running across the flakes, and a third cleavage occurs at about 70 degrees to the second cleavage. ... Average refractive index for sodium light ... is > 1.170 and < 1.715 , but is nearer the former value. ... Pleochroism distinctive ... absorption being moderately strong. The scheme is, parallel to X (that is, approximately, second cleavage) dirty green or olive-coloured, parallel to Y indigo to smoky-blue. The wisps show less well-marked changes of colour. The birefringence is usually very low, ultra-blues, ultra-browns and indigo tints ... occasionally first order greys and yellows are seen. Most of the flakes give a biaxial figure, the emergence of the acute bisectrix being almost central. The sign is positive, and the isogyres frequently show well-marked dispersion. The wisps show straight extinction on the length¹. Chloritoid from the shore sands of Brittany, observed by the author, is identified chiefly by its blue or bluish-green colour, high refractive index, low birefringence, strong pleochroism and dispersion of the optic axes, interference figure and sign, in all of which properties it agrees closely with the foregoing data. It tends to be scaly, showing a delicate, laminated structure, the 'wisp' varieties being less common. In very small grains its diagnosis is by no means always certain.

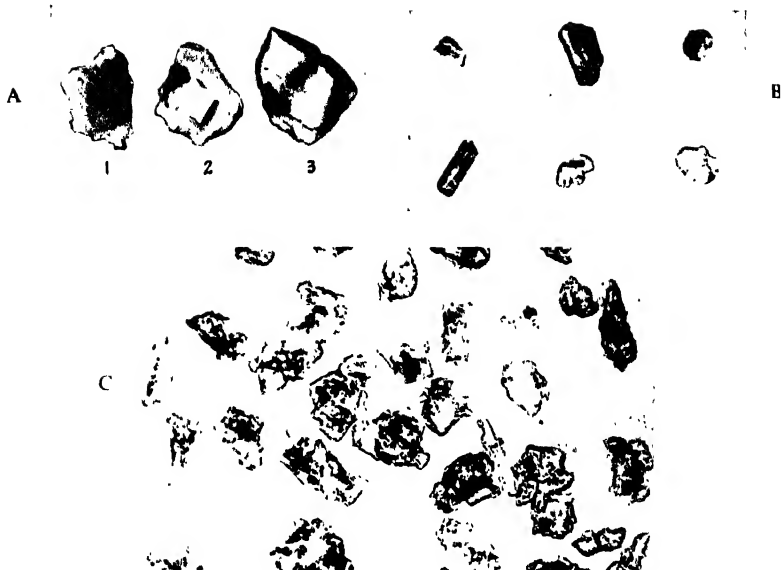
Occurrence. In sands of the Upper Lias-Lower Inferior Oolite of the West of England¹; in the Northampton Ironstone²; in the Cotteswold Sands and Inferior Oolite limestone at Shipton Moyne³; in the Jurassic sandstones of Yorkshire⁴; in the Upper Kimmeridge Clay and Portland Sand of Dorset, Wiltshire, Oxfordshire and Buckinghamshire⁵; in the Hunstanton Red rock⁶; in the lower part of the Great Ouse Basin⁷; from beds of sand and clay sampled from two borings in the plain of Lombardy, Northern Italy⁸; in shore sands from various localities in Southern Brittany⁹.

Possible Sources of Derivation. Crystalline schists, phyllites and quartzites. From reconstituted argillaceous sediments.

REMARKS.—The closely allied manganese-bearing silicate, Ottrelite, is fully described on p. 156.

References

- ¹ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 254.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 382.
- ³ P. G. H. Boswell, *Proc. Cotteswold Nat. Field Club*, **27**, 1923, p. 213.
- ⁴ R. H. Rastall, *Proc. Yorks. Geol. Soc.*, **22**, 1932, p. 93.
- ⁵ E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 250.
- ⁶ R. H. Rastall, *Geol. Mag.*, **67**, 1930, p. 436.
- ⁷ R. H. Rastall, *Quart. Journ. Geol. Soc.*, **82**, 1926, p. 116.
- ⁸ I. Chelussi, *Boll. Soc. geol. ital.*, **43**, 1924, p. 161.
- ⁹ Observations of F. T. Ingham and the author.



A-C. CALCITE

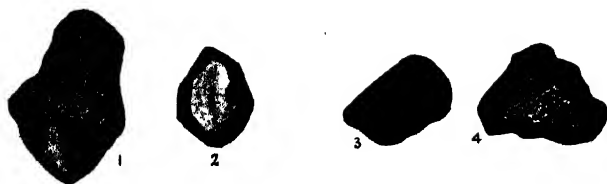
- A 1, 2 Upper Greensand, Chaldon Herring, Dorset [x 80]
 3 Shore Sand, Kynance, Cornwall [x 40]
 B Shore Sand, Dorset [x 23]
 C Fuller's Earth (Aptian), Surrey (*Authigenic*) [x 56]



D, E, F. CASSITERITE.

- D Typical Crystals and Fragments from Dartmoor (From brush-drawings by
 A Brammall) Grade-size up to 8 mm
 E Alluvials, Nigeria Transmitted light [x 36]
 F The same Reflected light

A



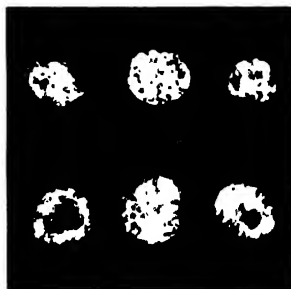
A. Ceylonite.

- 1, 2 Alluvials, Gold Coast, West Africa. [x 15]
 3 Pliocene, S. of F. Iham, Folkestone [x 30]
 4 From Monazite Sand, Travancore, India [x 25]

B



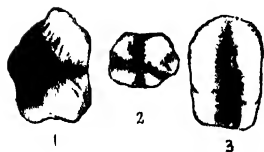
C



B, C Chalcedony.

- B Detrital Flint, Shore Sand, Sussex [x 31]
 C Corallian, Yorkshire (Authigenic) (x Nicols) [x 60]

D



F



F



D, E, F. Chiasolite

- D 1 Pleistocene Gravel, Bayford, Herts. [x 40]
 D 2, 3 Shooters Hill Gravel, London [x 40]
 E River Sand, R. Caldew, Cumberland [x 22]
 F Shore Sand, Cumberland [x 23]



A, B CHLORITOID.

- A 1 Shore Sand, Dinard, Brittany. [x 45]
 A 2, 3 Recent Sand, Le Pouldu, Brittany [x 45]
 B Locene, Virginia, U.S.A. [x 61]



C CHRYSOTILE

- 1 3 Shore Sand, Kynance, Cornwall [x 45]



CINNABAR
Diamondiferous Gravels, Bahia, Brazil
[Top & trans light, x 40]

General Reference

- P. G. H. Boswell, The Rarer Detrital Minerals of British Sedimentary Rocks, *Trans. Geol. Soc. Glasgow*, **18**, 1926-27, p. 138.
 F. Smithson, The Middle Jurassic Rocks of Yorkshire: A Petrological and Palaeographical Study, *Quart. Journ. Geol. Soc.*, **98**, 1942, p. 27 (chloritoid p. 33).

CHROMITE

(SPINEL GROUP)

Chem. Comp. FeCr_2O_4 .*System.* Isometric.*Habit.* Octahedral or combination of octahedron and dodecahedron.*Structure.* Rarely crystalline, commonly massive, granular.*Cleavage.* None.*Fracture.* Uneven.*Hardness.* 5.5.*Spec. Grav.* 4.32-4.57.*Lustre.* Metallic to submetallic, rarely dull.*Colour.* Black or brownish-black, frequently with purple tarnish.*Mag. Prop.* Moderately magnetic.*Elect. Prop.* Good conductor.

Opt. Prop. Opaque in transmitted light, except in very thin section when the deep brown colour and isotropic character are apparent.
 R.I. very high, $n = 2.070$.

Characters in Sediments. Occurs as rounded octahedral grains or as subangular and irregular fragments. Deposits derived from ultrabasic rocks often contain a high percentage of this mineral, which is identified chiefly by its grey submetallic lustre in vertical reflected light and by its colour and form. Locally in alluvial sands suitably derived.

Occurrence. In the Middle Chalk of Beer Head, S.E. Devonshire¹; ? in the dune sands of South Wales²; in shore sands of Kynance Cove, Coverack etc., Lizard district, Cornwall³; in the Titaniferous Iron-Sand of Porth Dulleyn, Carnarvonshire⁴; in the gabbro soil of Borneo⁵; in the sands of the Kettleman Hills, California, U.S.A.⁶.

Possible Sources of Derivation. Chiefly from peridotites, serpentines and associated ultrabasic rocks; more rarely from crystalline schists.

REMARKS.—The microscopical determination of chromite is not always convincing and, if possible, should be supplemented by chemical test. (With borax bead, chromium yields green colour in both oxidizing and reducing flames.)

References

- ¹ G. M. Davies, *Geol. Mag.*, 1919, p. 506.
- ² A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 321.
- ³ Author's observations.
- ⁴ T. H. Cope, *Proc. Liverpool Geol. Soc.*, **9**, 1902, p. 208.
- ⁵ D. Carroll, *Journ. Roy. Soc. West Australia*, **20**, 1933-34, p. 100.
- ⁶ M. N. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, **18**, 1934, p. 1559.

General References

- P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 273. (Record of chromite from sediments obtained on the 'Challenger' Expedition.)
 C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 367 and references cited (for alluvial chromite).

CHRYSOBERYL

Chem. Comp. BeAl_2O_4 .

System. Orthorhombic; dipyramidal.

Habit. Tabular \parallel (001); prismatic \parallel (100); commonly twinned about (130), contact and penetration; may be repeated to form pseudo-hexagonal crystals. Striated on (001) \parallel (100).

Structure. Crystalline.

Cleavage. Good \parallel (110); imperfect \parallel (010); poor \parallel (001).

Fracture. Conchoidal, irregular. Brittle.

Hardness. 8.5.

Spec. Grav. 3.75.

Lustre. Vitreous.

Colour. Various shades of green, yellowish green.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.747$, $\beta = 1.748$, $\gamma = 1.756$. Birefringence weak, $\gamma - \alpha = 0.009$. Optically biaxial, positive. Optic axial plane \parallel (010). $Z \approx c$, $bx \perp$ (001). Straight extinction. $2E = 84^\circ 43'$, $2V = 45^\circ 20'$. Dispersion $\rho > \nu$. Pleochroic: $Z =$ emerald green, $Y =$ orange yellow, $X =$ red.

Characters in Sediments. As rolled and flattened pebbles or grains in alluvial deposits, usually dull green in colour, often prismatic in form but with fractured edges from which a red 'glow' is sometimes discernible. Some alluvial examples exhibit a fine chatoyance (e.g. Ceylon gem gravels).

Occurrence. 'Often found as a detrital mineral, with diamond, corundum, garnet, cassiterite'¹; in diamond sands from near Sombula, Gwelo, S. Rhodesia²; abundant in gem-gravels, Ceylon³.

Possible Sources of Derivation. Granite pegmatite and aplite; mica schist; more rarely dolomite marble.

REMARKS.—Apparently so far unrecorded from British sediments and alluvials.

References

- ^{1, 2, 3} J. D. and L. S. Dana and others., *System of Mineralogy*, 7th ed., (Wiley, New York), 1955, p. 720.

General Reference

- W. L. Bragg and G. B. Brown, The Crystalline Structure of Chrysoberyl, *Proc. Roy. Soc., Lond., Ser. A*, 110, 1926, p. 34.

CHRYSOTILE

[Pl. 15C, between pp. 80–81]

Chem. Comp. $3\text{MgO} \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.*System.* Orthorhombic (?).*Habit.* Fibres, elongated \parallel c.*Structure.* Crystalline, fibrous.*Cleavage.* Poor \parallel (110) at 130° .*Fracture.* Irregular.*Hardness.* 4.*Spec. Grav.* 2.5.*Lustre.* Pearly, resinous.*Colour.* Green, yellow, grey. Translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.508$, $\beta = 1.512$, $\gamma = 1.522$. Birefringence moderate, $\gamma - \alpha = 0.014$. Optically biaxial, positive. Optic axial plane \parallel (010). $Bxa = Z \parallel c$, i.e. positive elongation. $X = b$. $2V = 30^\circ - 35^\circ$. Pleochroism faint, $Z = \text{green-yellow} > Y = \text{green to colourless} > X = \text{green to colourless}$.

Characters in Sediments. Chrysotile in sediments is characterized by its fibrous habit, yellow-green colour, low R.I., positive elongation and straight extinction, except in cases where anomalous 'ultra blue' interference colours may prevail. It differs from antigorite (p. 46) by its fibrous, rather than lamellar structure, and sign.

Occurrence. Recorded as 'Serpentine': In the Devonian and Culm sediments of the Torquay district¹; in the Permian rocks of the Torquay Promontory²; in the New Red Sandstones of the West of England³; in the sands of the Upper Lias-Lower Inferior Oolite of the West of England⁴; in the shore sands in proximity to the serpentine masses of the Lizard district, Cornwall⁵; in recent deposits of Pavia etc., Northern Italy⁶; in deposits of doubtful age (?Eocene) of Marazion, Cornwall⁷.

Possible Sources of Derivation. Serpentine rocks. Decomposition product of ferro-magnesian minerals.

REMARKS.—Most of the so-called 'serpentine' recorded from British sediments is probably chrysotile, far less commonly antigorite (p. 46) or it may be another member of the chlorite group (p. 78). See general note under Serpentine (p. 177).

References

- ¹ W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, pp. 139, 142.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, **38**, 1927, p. 134.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 239.
- ⁴ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 252.
- ⁵ Author's observations.
- ⁶ E. Tacconi, *Rend. R. Ist. lombardo*, ser 2, **34**, 1901, p. 873.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, pp. 213, 226.

CINNABAR

[Pl. 16, between pp. 80-81]

Chem. Comp. HgS.*System.* Hexagonal.*Habit.* Rhombohedral; tabular \parallel (0001); prismatic \parallel (10 $\bar{1}$ 0); often twinned about (0001).*Structure.* Crystalline, granular.*Cleavage.* Perfect \parallel (10 $\bar{1}$ 0).*Fracture.* Subconchoidal, irregular.*Hardness.* 2-2.5.*Spec. Grav.* 8.1.*Lustre.* Adamantine, metallic.*Colour.* Bright red (translucent) to lead-grey (opaque).*Mag. Prop.* —*Elect. Prop.* —*Opt. Prop.* R.I. very high, $\epsilon = 3.272$, $\omega = 2.913$. Birefringence extreme, $\epsilon - \omega = 0.359$. Optically uniaxial, positive. Rotatory power (circular polarization) extremely high, 315° for red. Absorption noted in some crystals.*Characters in Sediments.* The soft and sectile features of cinnabar result in production of irregularly shaped detrital grains (red, translucent), but in the more opaque (lead-grey) forms, traces of rhombohedral or prismatic faces may be perpetuated.*Occurrence.* In diamondiferous gravels of Bahia, Brazil¹; in gold placers of Dutch Guiana (as water-worn pebbles)².*Possible Sources of Derivation.* Veins and impregnations near recent volcanic rocks and hot springs (solfataric action).

REMARKS.—The optical properties of cinnabar are quite remarkable and diagnostic; so is the vermilion streak. Volatile, with deposition of metallic mercury in open tube.

*References*¹ J. C. Branner, *Amer. Journ. Sci.*, **31**, 1911, pp. 480-490.² J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), **1**, 1944, p. 254.*General Reference*J. C. Branner, Outlines of the Geology of Brazil, *Bull. Geol. Soc. Amer.*, **30**, 1919, pp. 189-338.

CLINOCHLORE

(CHLORITE GROUP)

Note: See also Chlorite, p. 78.*Chem. Comp.* 5MgO . (Al, Cr)₂O₃ . 3SiO₂ . 4H₂O.*System.* Monoclinic.*Habit.* Pseudohexagonal plates with bevelled edges; tabular, prominent basal plane. Polysynthetic twinning common.

Structure. Foliated, massive, rarely crystalline.

Cleavage. Perfect \parallel (001).

Fracture. Irregular.

Hardness. 2-3.

Spec. Grav. 2.76-2.78.

Lustre. Vitreous, pearly (001).

Colour. Green, olive, less commonly yellow, white.

Mag. Prop. Weakly to non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.579$, $\beta = 1.579$, $\gamma = 1.584$. Birefringence weak, $\gamma - \alpha = 0.005$. Optically biaxial, positive. (Negative form also known, with R.I. $\beta = 1.594$, birefringence 0.010.) Optic axial plane (010). $Bxa = Z \perp (001)$. Rarely $Z \wedge \perp (001) = 2^\circ 30'$ (*A. N. Winchell*). $2V = 0^\circ \pm$. Weak inclined dispersion $\rho < \nu$. Pleochroism $X = \text{pale green}$, $Y = \text{pale green}$, $Z = \text{pale yellow green}$.

Characters in Sediments. It is rare that clinochlore is specifically determinable in detrital sediments. The green grains of low R.I., weak birefringence (often 'ultra-blue') commonly met with are not clinochlore *per se* but of variable and complex composition, best designated 'chloritic matter'. Clinochlore is characterized by its green colour, weak but distinctive pleochroism, normally positive sign, low R.I. and birefringence. It is rarer than penninite (p. 158) and differs from that species particularly in the very low birefringence ('ultra-blue' abnormal interference colours) exhibited by the latter, not typical of clinochlore.

Occurrence. See p. 79 for records of detrital 'chlorite'.

Possible Sources of Derivation. Slates, phyllites and metamorphic rocks.

General Reference

J. Oreel, Recherches sur la Composition Chimique des Chlorites, *Soc. franc. minéralogie Bull.*, 50, 1927, p. 75.

CLINOZOISITE

(EPIDOTE GROUP)

Chem. Comp. $4\text{CaO} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Tabular \parallel (100), elongated \parallel b; striations \parallel b.

Structure. Crystalline.

Cleavage. Perfect \parallel (001). Imperfect \perp (100).

Fracture. Irregular.

Hardness. 6.5.

Spec. Grav. 3.35-3.38.

Lustre. Vitreous.

Colour. Colourless, yellow, pale green, brown.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.715$, $\beta = 1.720$, $\gamma = 1.725$. Birefringence moderate, $\gamma - \alpha = 0.010$. Optically biaxial, positive. (Negative forms

are known.) Optic axial plane \parallel (010). $Bxo = X$ inclined to c at 2° – 12° . $Bxa = Z$ inclined to (001) cleavage = 24° – 14° (*A. N. Winchell*). $Y = b$. $2V = 66^\circ$. $2E = 138^\circ$. Dispersion strong, $\rho < \nu$. Pleochroism $X = \text{green}$, $Y = \text{pink or green}$, $Z = \text{deep red or green}$. 'Ultra-blue' anomalous birefringence colours occasionally exhibited.

Characters in Sediments. Clinozoisite, though rarely recorded from sediments, is probably commoner than generally anticipated. It is of more frequent occurrence in other conditions than zoisite. Detrital grains are colourless or pale yellow, generally determined by (001) cleavage, having high R.I., moderate birefringence (occasional 'ultra-blue' interference tints) and weak pleochroism. Differs from zoisite in its oblique extinction (in (010) grains measured on cleavage traces) and larger optic axial angle. Inclusions may be amphibole microlites.

Occurrence. Dune sands, S. Wales¹; river and dune sands of Chinese Turkestan².

Possible Sources of Derivation. Crystalline schists, metamorphosed basic igneous rocks; also from sausserite, an alteration product of lime-soda felspar.

References

¹ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 321.

² A. Vendl, *Mitt. Jahrb. k.-ung-Geol. Austria*, **21**, 1913, p. 1.

COLLOPHANE

Chem. Comp. CaO , P_2O_5 , H_2O , CO_2 , etc.

System. Non-crystalline: amorphous.

Habit. Massive.

Structure. 'Stratified' -as deposited.

Cleavage. None.

Fracture. Conchoidal.

Hardness. 3.5.

Spec. Grav. 2.6–2.9.

Lustre. Dull.

Colour. White.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. variable, $n = 1.569$ – 1.63 . Optically isotropic, some examples weakly birefringent due to strain.

Characters in Sediments. Irregular, shapeless grains of white or grey colour, to be anticipated in certain 'phosphate' environments. Also in the form of rounded grains or 'pellets' not unlike large oolites.

Occurrence. Miocene limestone, Florida, U.S.A.; Pliocene and Quaternary deposits, Florida; shore deposits, Gulf Coast, Florida; Jacksonville, Florida; at Savannah and Brunswick, Georgia, U.S.A.; at Charleston, South Carolina, U.S.A.¹; at Tybee and St. Simon Island, Georgia²; in beach sands between St. John's River and St. Augustine, Florida, U.S.A.³

Later Records. In Magnesian Limestone, Durham⁴; in Northampton Sand Ironstone Field, Northamptonshire, etc.⁵; in Liassic Ironstones, Cleveland, Yorkshire⁶; in Thames Gravel⁷.

Possible Sources of Derivation. Phosphatic nodules, bones, phosphates in general.

REMARKS.—See also Chapter II, p. 274, and Chapter VI, p. 441.

References

- ¹ Communication from J. H. C. Martens, Florida State Geological Survey, to the author.
- ² J. H. C. Martens, *Bull. Geol. Soc. Amer.*, **46**, 1935, p. 1563.
- ³ J. H. C. Martens, *19th Ann. Rep. Florida State Geol. Surv.*, 1928, p. 130.
- ⁴ K. C. Dunham, G. F. Claringbull and F. A. Bannister, *Miner. Mag.*, **28**, 1948, p. 338.
- ⁵ J. H. Taylor, *Mem. Geol. Surv.*, 1949, p. 3.
- ⁶ T. H. Whitehead and ors., *Mem. Geol. Surv.*, 1952, p. 26.
- ⁷ S. E. Ellis and G. F. Claringbull, *Miner. Mag.*, **29**, 1951, p. 615.

COLUMBITE-TANTALITE

[Pl. 17, between pp. 96–97]

Chem. Comp. Columbite (Fe, Mn) (Cb, Ta)₂O₆.
Tantalite (Fe, Mn) (Ta, Cb)₂O₆.

System. Orthorhombic; dipyramidal.

Habit. Prismatic, short, moderately rectangular, usually terminated by pinacoids with or without (001); tabular || (100). Contact twins about (021) common, producing heart-shaped crystals, often striated on (100).

Structure. Crystalline.

Cleavage. Distinct || (100); inferior || (010).

Fracture. Subconchoidal, brittle. Common.

Hardness. 6.

Spec. Grav. Columbite 5·3, Tantalite 7·3 (varies with composition).

Lustre. Adamantine, brilliant to resinous. Bluish-steel tarnish (irridescence) frequently noted.

Colour. Black, grey, brownish black, Opaque. Occasionally translucent on thin edges.

Mag. Prop. Weakly magnetic.

Elect. Prop. Good conductors.

Opt. Prop. Observed in translucent grains or flakes. R.I. very high, $\alpha = 2\cdot26$, $\beta = 2\cdot29$, $\gamma = 2\cdot34$ (increases with decrease of Ta₂O₅). Birefringence strong, $\gamma - \alpha = 0\cdot08$. Optically biaxial, positive. Optic axial plane || (100). $Bxa - Z \perp (001)$. Dispersion strong, $\rho < \nu$, increasing with increase of Cb. $2V = 73^\circ - 75^\circ$ (less with decreasing Ta₂O₅). Straight extinction.

Characters in Sediments. As water-worn crystalline grains or pebbles, usually jet-black to grey in colour and of characteristic rectangular shape.

Occurrence. In alluvial deposits, Greenbushes, W. Australia¹; in alluvial deposits, associated with cassiterite and wolframite, Leruinn-Kano, Nigeria².

Possible Sources of Derivation. Granite, pegmatite, metalliferous lodes.

yielding good uniaxial figure. The colour is often unevenly distributed in the grains, some appearing very 'blotchy'. Such anomalous optical properties as may sometimes be noted are probably due to twinning.

Occurrence. In Silurian sediments near Melbourne, Australia (sapphire)¹; in the Pennant Sandstones, South Wales²; in the Coal Measures at Cwmgorse Valley, Wales³; in Coal Measure shale at Cow Gate, Newcastle (sapphire)⁴; in the Durham Coal Measures⁵; in the Kimmeridgian-Portlandian Sands, Buckinghamshire, etc.⁶; in the Portland Sand of Dorset⁷; in the Ashdown Sand (Wealden), Hastings, Sussex⁸; in the Sandgate Beds, Tilburstow Hill, Surrey⁹; in the Greensand and Eocene deposits of the Haldon Hills, Devonshire¹⁰; in the Pliocene of West Cornwall; in deposits of doubtful age at Marazion, Cornwall¹¹; in gem sands of Brittany (sapphire)¹²; in dune sands, Pointe de Grave (Landes) (sapphire)¹³; in the Beach Sands of New South Wales (sapphire)¹⁴; in surface deposits of S.E. Devonshire¹⁵; in Dartmoor detritals¹⁶; in sea-bottom deposits of the Gulf of Manaar¹⁷.

Later Records. In Beach Sands, Carbis Bay, Cornwall¹⁸.

Possible Sources of Derivation. Igneous or metamorphic rocks, especially contact-metamorphosed limestones. Alluvial deposits.

REMARKS.—The combination of a high R.I., often blotchy colouring and low birefringence aids identification. Of sporadic occurrence in detrital sediments; colourless or yellow varieties are the most common. Sapphire, the blue variety, is on the whole rare; ruby, the red variety, not so far recorded (detrital) according to the author's observations. Take care to distinguish from adventitious 'carborundum' which may have accidentally found its way into the heavy residue.

References

- ¹ W. G. Langford, *Proc. Roy. Soc. Victoria*, **29**, 1916, p. 40.
- ² A. Heard, *Geol. Mag.*, **60**, 1923, p. 83.
- ³ A. Stuart, in D. F. Davies, E. Dix and A. E. Trueman, *South Wales Inst. Eng.*, 1928, p. 131.
- ⁴ S. Tomkeieff, *Proc. Geol. Assoc.*, **38**, 1927, p. 518.
- ⁵ J. G. Kellett, *Proc. Univ. Durham Phil. Soc.*, **7**, 1926, p. 208.
- ⁶ E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 240.
- ⁷ M. P. Latter, *Proc. Geol. Assoc.*, **37**, 1926, p. 73.
- ⁸ H. B. Milner, *Proc. Geol. Assoc.*, **36**, 1925, p. 315.
- ⁹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.
- ¹⁰ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, pp. 216, 226.
- ¹¹ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ¹² C. Barrois, *Ann. Soc. Geol. Nord.*, **24**, 1896, p. 182.
- ¹³ R. Bréon, *Bull. Soc. franç. Min.*, **3**, 1880, p. 45.
- ¹⁴ H. F. Whitworth, *Journ. Roy. Soc.*, New South Wales, **65**, 1931, p. 59.
- ¹⁵ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 147.
- ¹⁶ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 44.
- ¹⁷ J. Lomas, in W. H. Herdman, Report on Pearl Oyster Fisheries of the Gulf of Manaar, *Roy. Soc.*, 1903.
- ¹⁸ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General References

- P. G. H. Boswell, The Rarer Detrital Minerals of British Sedimentary Rocks, *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 136.
 C. Raeburn and H. B. Milner, *Alluvial Prospecting*, (Murby, London), 1927, p. 375 (for alluvial corundum).
 A. E. Barlow, Corundum, its Occurrence, Distribution, Exploitation and Uses, *Canada Dept. Mines. Geol. Surv. Mem.*, 57, 1915.

CROSSITE

(AMPHIBOLE GROUP)

Chem. Comp. $\text{Na}_2\text{O} \cdot 4(\text{Mg, Fe})\text{O} \cdot (\text{Fe, Al})_2\text{O}_3 \cdot 8\text{SiO}_2$.

System. Monoclinic.

Habit. Prismatic.

Structure. Crystalline.

Cleavage. Perfect \parallel (110) at 124° .

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.16.

Lustre. Dull, resinous.

Colour. Bluish black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.65 \pm$, $\beta = ?$, $\gamma = 1.66 \pm$ (*A. N. Winchell*); $\beta = 1.670$ (*E. S. Larsen*). Birefringence moderate, $\gamma - \alpha = 0.01 +$ (*A. N. Winchell*). Optically biaxial, negative. Position of optic axial plane varies with composition, recorded both \parallel and \perp (010). Oblique extinction, $Z \wedge c = 3^\circ$, $Z \approx b$, $Y \wedge c$, small to moderate. Optic axial angle variable. Dispersion very strong, $\rho > \nu$. Pleochroism strong, $X =$ bright yellow or colourless, $Y =$ deep blue, $Z =$ violet.

Characters in Sediments. A very rare mineral in detrital sediments, but to be anticipated where soda-bearing amphiboles are diagnosed. Similar form to glaucophane (*q.v.* p. 113) *i.e.* quite irregularly shaped grains determined by (110) cleavage and exhibiting characteristic colour and pleochroism.

Occurrence. In siliceous shale (of Miocene or Pliocene age), Southern California, U.S.A.¹; in the San Onofre Breccia (Lower Miocene), California, U.S.A.².

Possible Sources of Derivation. Schist and contact metamorphic rocks.

REMARKS.—Crossite is a soda-bearing amphibole intermediate in composition between glaucophane (p. 113) and riebeckite (p. 173). Some previous identifications of glaucophane (p. 113) have probably been crossite (see N. Holgate, *Miner. Mag.*, 29, 1951, p. 792).

References

- ¹ R. D. Reed, *Journ. Geol.*, 36, 1928, p. 342.
² A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, 36, 1925, p. 159.

CYMATOLITE

(See Spodumene, p. 184)

DELESSITE

(CHLORITE GROUP)

Chem. Comp. $4(\text{Mg}, \text{Fe})\text{O}, 2\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 5\text{H}_2\text{O}$.*System.* Monoclinic.*Habit.* Spherulitic, lamellar.*Structure.* Crystalline.*Cleavage.* Good \parallel (001).*Fracture.* Irregular.*Hardness.* 2.*Spec. Grav.* $2.8 \pm$.*Lustre.* Vitreous, dull.*Colour.* Green, olive green, pink. Translucent.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Poor conductor.*Opt. Prop.* R.I. high, $\alpha = 1.605$, $\beta = 1.619$, $\gamma = 1.619$. Birefringence moderate, $\gamma - \alpha = 0.014$. Optically biaxial, negative. Optic axial $\angle c = 0^\circ - 7^\circ$. Pleochroism distinctive: X = pale green, yellow, colourless, Y = Z = green or pink.*Characters in Sediments.* Delessite is probably a rare species in detrital sediments, though not necessarily so in parent rocks. Its lamellar or spherulitic forms are characteristic, otherwise it is in many properties similar to penninite (*q.v.* p. 158). It differs from this mineral in its negative sign and higher R.I. 'Ultra-blue' anomalous interference colours rarely exhibited; more commonly delessite shows decided polarization colours.*Occurrence.* In certain deep sea deposits¹; in the Sands of Dancalia, Africa².*Possible Sources of Derivation.* Amygdaloidal basalt; rock cavities of all kinds; alteration products resulting from hydrothermal action on ferro-magnesian minerals.

REMARKS.—Delessite is essentially a ferriferous penninite.

References

¹ H.M.S. Challenger, Report on the Scientific Results of the Voyage of, 1891 (Admiralty).² E. Artini, *Atti Soc. ital. Sci. nat.*, 60, 1921, p. 371.

DIALLAGE

(VARIETY OF DIOPSIDE, *q.v.* p. 96)

DIAMOND

[Pl. 19, between pp. 96-97]

Chem. Comp. C.*System.* Isometric.*Habit.* Octahedral, dodecahedral, tetrahedral and modified forms.

Crystals often curved. Contact and penetration twins on (111), also on (001).

Structure. Crystalline.*Cleavage.* Perfect \parallel (111).*Fracture.* Irregular, conchoidal. Brittle.*Hardness.* 10.*Spec. Grav.* 3.52.*Lustre.* Adamantine to greasy.*Colour.* Colourless, white, yellow, orange, red, green, blue, brown, black. Transparent to translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. very high, $n = 2.419$. Optically isotropic. Abnormally shows uniaxial interference figure and interference colours in bands or centred about inclusions; due to strain and noted in twin crystals.*Characters in Sediments.* In clear, colourless octahedral grains with slight rounding of angles. Inclusions common, e.g. graphite, magnetite, iron ores, zircon, mica and gaseous. The deep coloured (brown and black) varieties are largely due to carbonaceous matter.*Occurrence.* In alluvial sands, British Guiana^{1,2}; in alluvial sands, South-West Africa³; in alluvial sands, Gold Coast, West Africa⁴; in alluvial sands, Somobula Forest, S. Rhodesia⁵.*Possible Sources of Derivation.* Peridotite and associated ultrabasic rocks; quartzose conglomerates of suitable provenance; pegmatite veins; alluvial deposits; glacial drift.

REMARKS.—Rare in detrital sediments unless in environments including diamondiferous rocks. 'Bort' is the spherical type with roughened surface, often radiating, fibrous structure; 'Bywater' is the yellow variety: 'Carbonade' is the black diamond, opaque, without cleavage, compact or massive.

*References*¹ L. T. Emory, *Eng. Min. Journ. Press*, **115**, 1923, p. 571.² L. J. Spencer, *Miner. Mag.*, **20**, 1924, p. 186.³ J. W. Finch, *Eng. Min. Journ. Press*, **113**, 1922, p. 317.⁴ A. E. Kitson, *Govt. Gold Coast Accra, Rep. Geol. Surv.*, 1922-23.⁵ A. M. MacGregor, *S. Rhodesian Geol. Surv. Bull.*, **8**, 1923, p. 38.*General References*M. Bauer, *Precious Stones* (Trans. L. J. Spencer), 1904, p. 113.F. P. Mennell, Note on the Colours of Some Alluvial Diamonds, *Miner. Mag.*, **14**, 1906, p. 202.W. Crook, *Diamonds*, London, 1909.W. R. Cattelle, *The Diamond*, New York, 1911.J. R. Sutton, *Diamond, a Descriptive Treatise*, (Murby, London), 1928.

DIASPORE

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$. Also with Mn and Fe.

System. Orthorhombic.

Habit. Prismatic, flattened \parallel (010); elongated \parallel c.

Structure. Crystalline, massive.

Cleavage. Perfect \parallel (010); distinct \parallel (210).

Fracture. Uneven.

Hardness. 6.5–7.

Spec. Grav. 3.4–3.5.

Lustre. Pearly, dull.

Colour. White, grey, pink, red.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.702$, $\beta = 1.722$, $\gamma = 1.750$. Birefringence strong, $\gamma - \alpha = 0.048$. Optically biaxial, positive. Optic axial plane \parallel (010). $Bxa = Z = a$, $X = c$. Straight extinction. $2V = 84^\circ$. Dispersion weak, $\rho < \nu$. Pleochroism noted in some examples, $X = Y =$ colourless, $Z =$ blue; or $X =$ violet or red brown, $Z =$ yellowish white.

Characters in Sediments. An uncommon species in detrital sediments, but where diagnosed, tends to grains of prismatic form, determined largely by (010) cleavage, with uneven terminations. Characterized by colour, pleochroism, high R.I. and strong birefringence and optic axial plane \parallel cleavage. To be anticipated in sediments containing bauxite and corundum.

Occurrence. In clays from various stratigraphical horizons of the Cambrian, Carboniferous and Upper Cretaceous, U.S.A.¹; in the sands from Limoero, Bahia, Brazil²; in the shore sands of the Adriatic coast³; in the sands of the coast of Tuscany, Italy⁴; in association with diamonds and carbonados in the state of Bahia, Brazil⁵; in the sands of the Tyrrhenian coast, Italy⁶.

Possible Sources of Derivation. Volcanic rocks (with alunite); schists; bauxite deposits.

References

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³ I. Ricciardi, *Atti. Soc. ital. Sci. nat.*, **33**, 1890, p. 41.

⁴ I. Chelussi, *Boll. Soc. geol. ital.*, **29**, 1910, p. 207.

⁵ J. C. Branner, *Amer. Journ. Sci.*, **31**, 1911, p. 480.

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DICKITE*

(KAOLINITE GROUP)

[Pl. 20A, between pp. 96–97]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic.

* See also Ch. III, p. 310.

Habit. Hexagonal basal plates (001) and rouleaux.

Structure. Crystalline, scaly.

Cleavage. Perfect \parallel (001).

Fracture. Uneven.

Hardness. 2.

Spec. Grav. 2.6.

Lustre. Pearly, glistening.

Colour. White.

Mag. Prop. Non-magnetic.

Elect. Prop. ?

Opt. Prop. R.I. low, $\alpha = 1.561$, $\beta = 1.563$, $\gamma = 1.567$. Birefringence weak, $\gamma - \alpha = 0.006$. Optically biaxial positive. Optic axial plane \perp (010). $Bxa = Z = b \perp$ (010). $Y \wedge a = 11^\circ - 16^\circ$. $X \wedge c = 15^\circ - 20^\circ$. $2V = 52^\circ - 80^\circ$. Often pleochroic when stained: see *Gen. Ref.* below (F. Smithson and G. Brown). Dispersion strong, $\rho < \nu$.

Characters in Sediments Generally occurs as very small hexagonal flakes, white in colour and with glistening lustre. Liable to be confused with kaolinite, but distinguished by position of *Bxa* and positive character which are different from that mineral (p. 130).

Occurrence. Coal Measure shale, Cow Gate, Newcastle¹; certain clays and limestones, Columbia, Missouri, U.S.A.².

Later Records. In Lower Carboniferous Sandstone, Anglesea and Caernarvonshire³; in Millstone Grit, Anglesey, Staffordshire and Yorkshire⁴; in Magnesian Limestone, Durham⁵; in Middle Jurassic Sandstones, Yorkshire⁶.

Possible Sources of Derivation. Ball clay, china clay and kaolinite-bearing clays.

References

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- ² W. A. Tarr and W. D. Keller, *Amer. Mineral.*, **21**, 1936, p. 109.
- ³ G. Brown and F. Smithson, *Nature*, **172**, 1953, p. 317.
- ⁴ G. Brown and F. Smithson, *loc. cit.*
- ⁵ K. C. Dunham, G. F. Claringbull and F. A. Banister, *Miner. Mag.*, **28**, 1948, p. 338.
- ⁶ G. Brown and F. Smithson, *loc. cit.*

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- C. S. Ross and P. F. Kerr, The Kaolin Minerals, *U.S. Geol. Surv., Prof. Paper*, 165-E, 1931.
- J. E. Hemingway and G. W. Brindley, The Occurrence of Dickite in some Sedimentary Rocks, *Proc. 18th Inter. Geol. Congress*, Part 13, 1948, p. 308.
- F. Smithson, The Petrography of Dickitic Sandstones in North Wales and Northern England, *Geol. Mag.*, **91**, 1954, p. 177.
- F. Smithson and G. Brown, Dickite from Sandstones in Northern England and North Wales, *Miner. Mag.*, **31**, 1957, p. 381.

DIOPSIDE

[Pl. 20B, between pp. 96-97]

(PYROXENE GROUP)

Chem. Comp. $\text{CaO} \cdot \text{MgO} \cdot 2\text{SiO}_2$.*System.* Monoclinic.*Habit.* Prismatic, more rarely tabular or bladed; sometimes twinned about (100) or (001).*Structure.* Crystalline.*Cleavage.* Always \parallel (110); sometimes \parallel (100), rarely \parallel (010). Parting \parallel (001) in twinned crystals. Parting on (100) well developed in diallage variety.*Fracture.* Uneven: often shown by irregular cracks traversing the crystal.*Hardness.* 5-6.*Spec. Grav.* 3.11-3.42.*Lustre.* Vitreous, sometimes resinous.*Colour.* Colourless, pale green, white or grey.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Moderate conductor.*Opt. Prop.* R.I. high, $\alpha = 1.664$, $\beta = 1.671$, $\gamma = 1.694$. Birefringence strong, $\gamma - \alpha = 0.030$. Optically biaxial, positive. $2V = 59^\circ$. Optic axial plane \parallel (010). $Bxa = Z$ inclined at $38^\circ 30'$ to c axis (varies). Oblique extinction: angle 38° to 45° (measured from c in the plane (010)). $Y \parallel b$. Tabular grains \parallel (100) give straight extinction \parallel first cleavage. Slight dispersion of bisectrices: $\rho > v$. Non-pleochroic.*Characters in Sediments.* Detrital diopside is distinguished chiefly by its tendency to occur in colourless to grey or pale green grains, by its refractive index, high polarization colours and oblique extinction angle (higher than kyanite, with which, in the absence of cleavage traces in that mineral, it is liable to confusion). Incipient alteration to a chlorite species, bastite, calcite and/or epidote may sometimes be noted. Inclusions of ilmenite, magnetite and apatite are not uncommon.*Occurrence.* In the Llandeilo sandstone of Glyn¹; in the wind-blown sands of Pembrokeshire (Newgale)²; in the dune sands of South Wales³; in the shore sands of the Lizard, Cornwall²; sands and clays sampled from two borings in the plain of Lombardy, Northern Italy⁴; various foreign Tertiary sands rich in pyroxene minerals²; in the coastal sands of Carnarvonshire⁵; in beach sands of Cedar Point, Ohio, U.S.A.⁶.*Possible Sources of Derivation.* Igneous rocks, especially of a basic type. Gneiss, schist and contact metamorphic rocks.

REMARKS.—'Diallage' is a distinctive variety of diopside, characterized by prominent parting on (100) and usually 'schillerization', superficial interference effect due to formation of thin oxide or hydrate films in surface cracks (solution along parting planes). This property it shares with bronzite (p. 101), the orthorhombic pyroxene, but differs from that

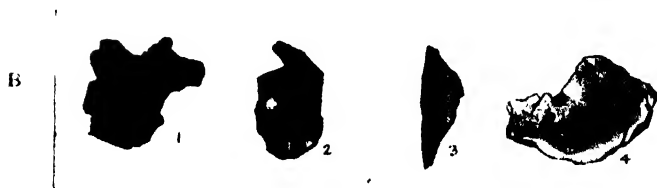


COLUMBITE

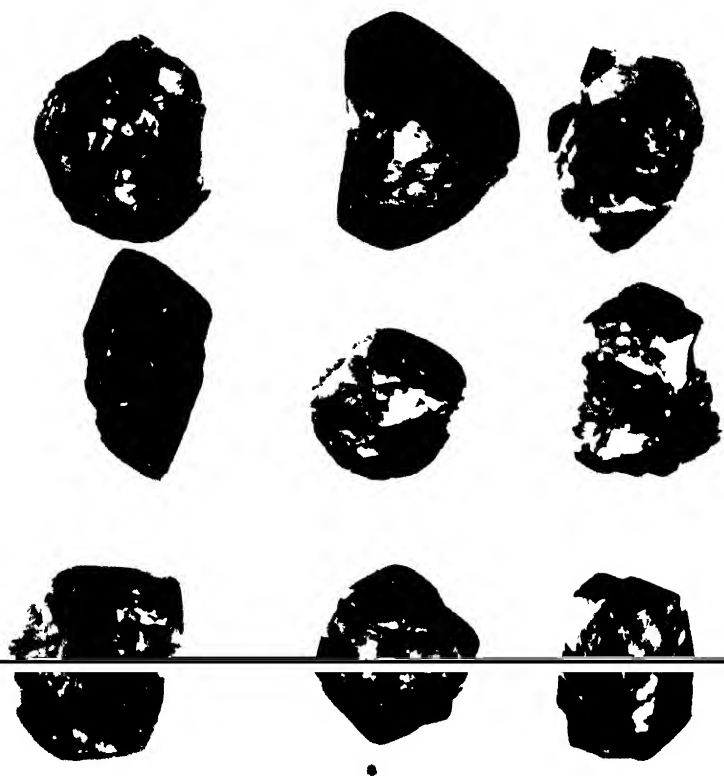
Alluvials, Terai District, Nigera
[Top & trans light x 40]



A. CORDIERITE.
Swettor, Dartmoor [x 24]

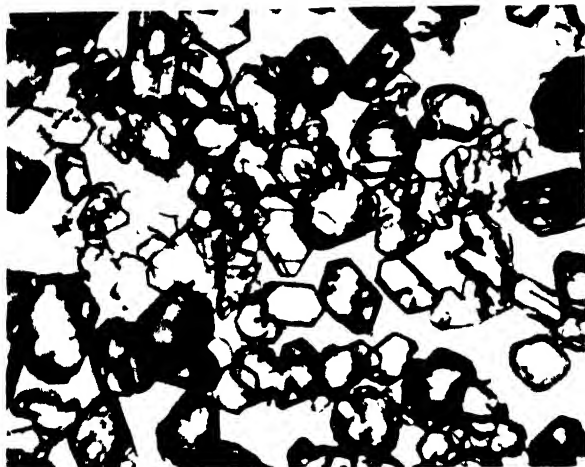


B. CORUNDUM.
1, 3, 4 Pliocene Sand, St. Keverne, Cornwall [1, 3, x 60] [4, x 55]
2 Miocene Sand, Los Angeles, Calif., U.S.A. [x 50]



DIAMOND.

Alluvials, Ghana. [Top & trans-light $\times 15$]



A. DICKITE.

Millstone Grit, Bodorgan, Anglesey [x 480]



B. DIOPSIDE

- 1 Miocene Sand, Santa Fe Springs, Calif. U.S.A. [x 45]
- 2 Shore Sand, Kynance Cove, Cornwall [x 45]
- 3 Shore Sand, Speeton, Yorks. [x 45]



C, D. DOLOMITI

- C Portland Sand, Dorset [x 55]
- D River Sand, Tyrol [x 28]

mineral in its oblique extinction. Diallage has a platy character, irregular outline, bronze-like lustre and is full of inclusions. In ferri-ferous varieties it is pleochroic, X = green, Y = brown, Z = green. Detrital diallage should be looked for in recent sediments whose provenance is associated with basic rocks of a gabbro type, *e.g.* shore sands, Lizard district, Cornwall.

References

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- ² Author's observations.
- ³ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 324.
- ⁴ I. Chelussi, *Boll. Soc. geol. ital.*, **43**, 1924, p. 161.
- ⁵ S. A. Billingham, *Geol. Mag.*, **66**, 1929, p. 289.
- ⁶ F. J. Pettijohn and J. D. Ridge, *Journ. Sed. Pet.*, **3**, 1933, p. 92.

DOLOMITE

[Pl. 20C, D, *between pp.* 96-97]

Chem. Comp. (Ca, Mg)CO₃.

System. Trigonal.

Habit. Simple rhombohedron (10 $\bar{1}$ 1) often curved; also irregular. Twinned about (01 $\bar{1}$ 2).

Structure. Crystalline, massive.

Cleavage. Perfect \perp unit rhombohedron (10 $\bar{1}$ 1). Parting \parallel (01 $\bar{1}$ 2).

Fracture. Conchoidal, but seldom observed.

Hardness. 3.5-4.

Spec. Grav. 2.8-2.9.

Lustre. Vitreous, pearly.

Colour. Colourless, white, greenish-white, brown and reddish-brown. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low for ϵ , high for ω . $\omega - \epsilon = 1.681$, $\epsilon = 1.500$; ω and ϵ vary with amount of FeCO₃ present (See *Ankerite*, p. 43). Birefringence very strong, $\omega - \epsilon = 0.181$. Optically uniaxial, negative. Usually shows a partial figure. Non-pleochroic.

Characters in Sediments. Chiefly recognized as grains by simple rhombohedral habit (rare in calcite), characteristic 'twinkling' (on rotation of polarizer) and sometimes by its zoning; almost invariably of secondary origin, hence tends to exhibit its rhombohedral character conspicuously.

Occurrence. In the Silurian Rocks of Southern Scotland¹; in Devonian limestones, Torquay district²; in the Trias of East Cheshire³; in the Keuper Marls of Charnwood, Leicestershire⁴; in the Portland Sand of Dorset⁵; in the North Sea Drift (from Overstrand to Heydon), Norfolk⁶; in the Dune Sands of South Wales⁷; in river sands from the Ure and the Ouse⁸.

Later Records. In St. Bees Sandstone, Cumberland and Furness⁹.

Possible Sources of Derivation. Derived dolomite is very rare, but if present is probably traceable to dolomitic limestone close at hand; in sediments is generally authigenic.

REMARKS.—Owing to its higher gravity than calcite, dolomite tends to come down with the 'heavy' crop separated with bromoform. It is practically insoluble in cold hydrochloric acid, also in acetic acid, but is soluble in these reagents if warm. For differentiating tests from calcite, see p. 67. The variety '*Ankerite*' (q.v. p. 43) is characterized by the presence of iron replacing some of the magnesium.

References

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 150.
- ³ H. W. Greenwood, *Proc. Liverpool Geol. Soc.*, **12**, 1920, p. 325.
- ⁴ T. O. Bosworth, *Keuper Marls Around Charnwood, Leicester Lit. and Phil. Soc.*, 1913, p. 81. Also C. G. Cullis, *Rep. Brit. Assoc.*, 1907, Leicester, p. 506.
- ⁵ M. P. Latter, *Proc. Geol. Assoc.*, **37**, 1926, p. 85.
- ⁶ P. G. H. Boswell, *Proc. Geol. Assoc.*, **27**, 1916, p. 92.
- ⁷ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 322.
- ⁸ S. Melmore, *Geol. Mag.*, **63**, 1926, p. 268.
- ⁹ K. C. Dunham and W. C. C. Rose, *Proc. Geol. Assoc.*, **60**, 1949, p. 27.

DUMORTIERITE

[Vol. 1, Pl. 8B, facing p. 242, and Pl. 21A between pp. 112-113]

Chem. Comp. $8\text{Al}_2\text{O}_3 \cdot \text{B}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Prismatic. Sometimes twinned about (110); also interpenetrated.

Structure. Crystalline; or in fibrous or columnar aggregates.

Cleavage. Good \parallel (100), less distinct \parallel (110). Parting observed \parallel (001).

Fracture. Uneven, but tends to coincide with parting planes.

Hardness. 7.

Spec. Grav. 3.26-3.36.

Lustre. Vitreous.

Colour. Colourless, greenish-blue, blue, grey, yellow-green, purple-grey, mauve. Transparent to translucent.



FIG. 38. Dumortierite from Dartmoor Granite (A. Brammall).

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.678$, $\beta = 1.686$, $\gamma = 1.689$. Birefringence moderate, $\gamma - \alpha = 0.011$. Optically biaxial, negative. $2V = 30^\circ - 40^\circ$. $2E = 52^\circ - 70^\circ$. Optic axial plane $\parallel (010)$. $Bxa = X \parallel c \perp (001)$. $Y \parallel b$, $Z \parallel a$. Straight extinction. Strong dispersion, $\rho > \nu$ or $\rho < \nu$. Pleochroism marked: $X =$ deep blue, $Y =$ yellow-violet, $Z =$ colourless or green. Maximum absorption both with crystalline and fibrous varieties \parallel vibration direction of polarizer (E-W).

Characters in Sediments. Presents unevenly terminated prismatic grains, sometimes with conspicuous striations \parallel prism edge. The resemblance to tourmaline is marked, especially in colour, but the refractive index of dumortierite is higher. Pleochroism is the chief diagnostic feature, the colour-change being very strong indeed, maximum absorption being as shown in Fig. 38 above. It is sometimes found as inclusions in cordierite (p. 88), when it is surrounded with pleochroic halos. Incipient alteration to muscovite is noted.

Occurrence. In the Bridport Sands (Inferior Oolite), West Bay, Dorset¹; in Sandstone of the Weald Clay, Surrey²; in the Lower Greensand of the Dorking-Leith Hill district³; in the Upper Greensand, Lulworth Cove, Dorset⁴; in the Gault Clay, Lulworth Cove, Dorset⁵; in the Blackheath Beds, Shirley, Surrey⁶; in the Bagshot Beds of Bournemouth, Hampshire⁷; in the Bagshot Beds, Wimborne, Dorset⁸; Late Tertiary-Quaternary Sands, San Joaquin Valley, California, U.S.A.⁹; in the Eocene of Great Haldon, Devonshire¹⁰.

Possible Sources of Derivation. Granite pegmatite; gneiss; metamorphic rocks.

REMARKS.—A. W. Groves has pointed out that most of the dumortierite he has found in English sediments is of a 'Stephens Ink' blue colour. In all cases the greatest care is necessary in diagnosis, implying accurate optical measurements, to prevent any possible confusion with blue tourmaline, etc.

N.B.—Keen search for detrital dumortierite in British sediments was made following the records published by A. W. Groves (1928). The discovery by J. N. Montgomery of a grain in the Neolithic silts of Piltdown, Sussex, is of particular interest. This example is colourless, with strong violet absorption, thus differing from H. A. Hayward's Wealden examples and from those found by A. W. Groves. The only known occurrence of similar dumortierite to that of the Piltdown grain is in the Land's End granite, according to A. W. Groves' observations. Other records since the above are from the Lower Greensand, Aylesbury, Buckinghamshire, and from the Oligocene of Totland Bay, I.O.W., by G. C. Flower and M. H. Lowson respectively (Royal School of Mines, London, 1928/29).

References

¹ A. W. Groves, *Miner. Mag.*, 21, 1928, p. 489.

² H. A. Hayward, Recorded in H. B. Milner, Supplement to Sedimentary Petrography, (Murby, London), 1926, p. 64; A. W. Groves, *loc. cit.*, p. 489.

³ H. A. Hayward, *Proc. Geol. Assoc.*, 43, 1932, p. 1.

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5, 10 A. W. Groves, personal communication.

9 R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, **11**, 1927, p. 363.

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A. Brammall, Dartmoor Detritals, *Proc. Geol. Assoc.*, **39**, 1928, p. 43.

W. Mackie, *Rep. Brit. Assoc.*, 1928 (*Glasgow*), 1929, p. 556.

ENIGMATITE

Chem. Comp. $2\text{Na}_2\text{O} \cdot 9\text{FeO} \cdot (\text{Al}, \text{Fe})_2\text{O}_3 \cdot 12(\text{Si}, \text{Ti})\text{O}_2$.

System. Triclinic.

Habit. Prismatic, vertically elongated. Twinning on (010), sometimes lamellar.

Structure. Crystalline.

Cleavage. Distinct \parallel (110) and (1 $\bar{1}$ 0). Cleavage angle 114° .

Fracture. Irregular.

Hardness. 5.5.

Spec. Grav. 3.74-3.85.

Lustre. Vitreous.

Colour. Black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\beta \approx 1.80$. Birefringence weak, $\gamma - \alpha = 0.006$.

Optically biaxial, positive. Optic axial plane nearly \parallel (010). $Bxa \approx Z$ inclined at 45° to c and 4° to (100). Y near b . Length of prism fast. $2V = 32^\circ$. $2E = 59^\circ$. Dispersion $\rho < \nu$? Intensely pleochroic, $X \approx$ reddish brown $< Y \approx$ dark brown $< Z \approx$ very dark brown.

Characters in Sediments. Diagnosed chiefly by its intense brown or brownish black colour, high relief, oblique extinction (4° to prismatic cleavage) and strong, distinctive pleochroism.

Occurrence. Dune sands, S. Wales¹; in shore sands, S. Coast, Greenland².

Possible Sources of Derivation. Nepheline-syenites and allied rocks.

REMARKS.—Enigmatite is a rare species and to be anticipated in sediments only where alkaline petrographic provinces are laid under contribution. A closely allied species is 'rhoenite', where the alkali is reduced to a minimum; it has similar properties to enigmatite and is normally found in basic igneous rocks.

References

¹ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 325.

² R. D. Crommelin, *Meddelelser om Grønland*, **113**, 1937.

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C. Palache, Crystallographic Notes on Anapaite, Ainigmatite and Eudidymite, *Zeitschr. für Kristallographie (A)*, **Band 86**, Heft 3/4, 1933, p. 280.

ENSTATITE

(PYROXENE GROUP)

[Pl. 21B, C, between pp. 112-113]

Chem. Comp. MgSiO_3 .*System.* Orthorhombic.*Habit.* Prismatic, bipyramidal. Twinning rare on (014) or (101).*Structure.* Crystalline.*Cleavage.* Good \parallel (110) at 88° . Parting on (010), (100), rarely (001).*Fracture.* Uneven.*Hardness.* 5-6.*Spec. Grav.* 3.1-3.3.*Lustre.* Vitreous to pearly; dull submetallic (bronze-like) in *bronzite*.*Colour.* Grey, yellow, greenish-white or olive green. Transparent to translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.650$, $\beta = 1.653$, $\gamma = 1.658$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial, positive. Optic axial plane \parallel (010). Length slow. $Bxa = Z \perp$ (001). Straight extinction $2V = 70^\circ$. $X \parallel$ a fast, $Y \parallel$ b, $Z \parallel$ c slow. Optic axial dispersion slight: $\rho < \nu$. Pleochroism faint in the normal mineral (thick grains), stronger with increase of iron; $X =$ yellow, $Y =$ brownish-yellow, $Z =$ green; distinctive for hypersthene (*q.v.*). *Bronzite* is an iron-bearing enstatite with optical properties intermediate between those of enstatite and hypersthene.

Characters in Sediments. Enstatite occurs in irregular or prismatic grains characterized by a somewhat 'dirty' colour, vitreous or pearly lustre of cleavage flakes (most grains tend to be (101) flakes), straight extinction, high refractive index and low birefringence (lower than hypersthene); also by its lack of pleochroism (in thin grains), which, together with its positive sign, serves to distinguish it from that mineral. Inclusions of magnetite, apatite or zircon are common, while alteration to a fibrous or lamellar aggregate (*bastite*) is not uncommon. The submetallic lustre acquired by cleavage flakes of enstatite, together with the bronze colour, are due to internal decomposition, whereby oxide of iron tends to occupy cleavage cracks producing the characteristic 'Schiller-spath' or Schiller-structure, by which properties *bronzite* is diagnosed; further alteration to chlorite minerals frequently observed in detrital *bronzite*.

Occurrence. Silurian Rocks of Southern Scotland¹; Middle and Upper Old Red Sandstone of Scotland²; North Sea drift and Upper Glacial Brick-earth, East Anglia³; shore sand of Kynance Cove and other places, Lizard, Cornwall⁴; coastal sands of Carnarvonshire⁵; various foreign alluvial deposits, soils, etc.⁶

Possible Sources of Derivation. Basic and ultrabasic igneous rocks; less commonly metamorphosed sedimentary rocks.

REMARKS.—It should be noted that pure enstatite is non-magnetic and can therefore be separated from hypersthene by electro-magnetic

treatment. The mineral is not attacked by hydrochloric acid, but hypersthene is less stable in this respect. 'Bastite' often develops as a pseudomorph after enstatite whereby the perfect (001) cleavage of antigorite (p. 46), of which bastite is but a coarse variety, is made parallel to the (010) parting of enstatite.

References

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (*Glasgow*), 1929, p. 556.
- ² W. Mackie, *Trans. Edinburgh Geol. Soc.*, **11**, 1923, p. 138.
- ³ P. G. H. Boswell, *Proc. Geol. Assoc.*, **27**, 1916, p. 79.
- ⁴ Author's observations.
- ⁵ S. A. Billingham, *Geol. Mag.*, **66**, 1929, p. 289.
- ⁶ E. Tacconi, *Rend. R. Ist. lombardo*, **34**, 1901, p. 873.

EPIDOTE (PISTACITE)

(EPIDOTE GROUP)

[Pl. 22A, B, between pp. 112-113]

Chem. Comp. $4\text{CaO} \cdot 3(\text{Al}, \text{Fe})_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Prismatic. Elongated \parallel b with dissimilar terminations. Often striated \parallel b. Frequently twinned about (100), rarely on (001).

Structure. Crystalline, fibrous, massive.

Cleavage. Perfect basal \parallel (001). Imperfect \parallel (100).

Fracture. Uneven.

Hardness. 6-7.

Spec. Grav. 3.25-3.5.

Lustre. Vitreous, sometimes resinous.

Colour. Greenish-yellow, dark green, shades of brown, grey.

Mag. Prop. Weakly magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.722$, $\beta = 1.742$, $\gamma = 1.750$. Birefringence strong, $\gamma - \alpha = 0.028$. Optically biaxial, negative. Optic axial plane \parallel (010) \perp principal cleavage. $Bxa = X$ inclined at $0^\circ - 5^\circ$ to c. $Y \parallel b$. $2V = 92^\circ$ (varies with amount of Fe_2O_3 present). Pleochroism weak: $Y =$ greenish-yellow \searrow $Z =$ colourless \searrow $X =$ colourless, pale green, noticeable in thick grains. Strong dispersion, $\rho > \nu$.

Characters in Sediments. Irregular and rather angular grains common, the platy forms often exhibiting partial (compass-needle) interference figure, due to emergence of one optic axis. Pale yellowish-green subangular grains, like small chips of broken 'bottleglass', are very characteristic of many sands and are remarkable for their transparency. A further diagnostic feature is the brilliant green-purple-red (ringed) interference tints observed in most clear individuals.

Occurrence. In the Old Red Sandstone of the West Midlands¹; in the Permian Rocks of the Torquay Promontory²; in the Upper Lias—Lower Inferior Oolite of the West of England³; in the Northampton Ironstone⁴; in the Sandgate Beds of Surrey⁵; in the Upper Greensand of Surrey⁶; in Eocene and Oligocene sands of the Haldon Hills and

Bovey Tracey respectively, Devonshire⁷; in the Bagshot Beds of Essex⁸; in Miocene-Pliocene sands of California⁹ (some of the Pliocene oil-sands of the Los Angeles Basin are particularly rich in epidote¹⁰); in the Pliocene deposits of West Cornwall¹¹; in the later Tertiary deposits of East England¹²; in surface deposits of S.E. Devonshire¹³; in dune sands of South Wales¹⁴; in blown sands, New-gale, Pembrokeshire¹⁵.

Later Records. In Downtonian, Tenbury, Worcestershire¹⁶; in Lower Greensand, W. Weald¹⁷; in Beach sand, Carbis Bay, Cornwall¹⁸.

Possible Sources of Derivation. Crystalline metamorphic rocks, especially altered impure limestones. Also from highly altered igneous rocks originally rich in ferro-magnesian minerals.

REMARKS.—In certain local environments, involving crystalline schists, amphibolites, etc., as contributors to sedimentary deposits, detrital zoisite (p. 206) (the orthorhombic member of the epidote group) may be met with; detrital clinozoisite is also known in sediments (p. 85).

References

- ¹ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 513.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, **38**, 1927, p. 135.
- ³ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 262.
- ⁴ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 383.
- ⁵, ⁶ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, p. 84.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ⁸ S. W. Wooldridge, *Proc. Geol. Assoc.*, **35**, 1924, p. 376.
- ⁹ R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol.*, **11**, 1927, p. 359.
- ¹⁰ Author's observations.
- ¹¹ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 361.
- ¹² I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 340.
- ¹³ W. G. Shannon, *Geol. Mag.*, **64**, 1927, pp. 147, 149.
- ¹⁴ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 324.
- ¹⁵ Author's observations.
- ¹⁶ P. S. Walder, *Proc. Geol. Assoc.*, **52**, 1941, p. 247.
- ¹⁷ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
- ¹⁸ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General Reference

- M. L. Goldman, *Amer. Journ. Sci.*, **39**, 1915, p. 277 (for significance of scarce epidote in sediments, as exemplified by the Catahoula Sandstone of Texas).

ESCHYNITE

Chem. Comp. [(Ce, Ca, Fe², Th)(Ti, Cb)₂O₆]

System. Orthorhombic; dipyrarnidal.

Habit. Prismatic (001); tabular (010); striated (100).

Structure. Crystalline.

Cleavage. Trace || (100).

Fracture. Conchoidal, brittle.

Hardness. 5–6.

Spec. Grav. 5.19.

Lustre. Submetallic or dull.

Colour. Black, brown, yellow.

Mag. Prop. Weakly to non-magnetic.

Elect. Prop. —

Opt. Prop. Opaque to brown translucent in small grains. R.I. very high, $n = 2.26$.

Characters in Sediments. Rolled prismatic or tabular, blackish brown grains and pellets.

Occurrence. In gold-bearing sands, Orenburg district, S. Urals, U.S.S.R.¹.

Possible Sources of Derivation. Nepheline syenite; granite pegmatite.

REMARKS.—A rare-earth mineral confined (in sediments) chiefly to alluvial deposits in suitable environments. Should be confirmed by chemical and spectrographic tests. Closely allied to Priorite [(Y, Er, Ca, Fe², Th)(Ti, Cb)₂O₆] see ref. ¹ below.

Reference

¹ J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, p. 796, and refs. there cited.

EUCLASE

[Pl. 22C, between pp. 112–113]

Chem. Comp. $\text{BeAlSiO}_4\text{OH}$ or $2\text{BeO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Prismatic, but often with numerous modifications.

Structure. Crystalline.

Cleavage. Perfect $\parallel (010)$; less distinct $\parallel (100)$ and (010) .

Fracture. Conchoidal, irregular; often brittle.

Hardness. 7.5.

Spec. Grav. 3.0–3.1.

Lustre. Vitreous.

Colour. Pale green, blue, light brown; sometimes colourless; transparent to opaque. (For opaque material, see ref. L. J. Spencer below.)

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor. Some crystals when rubbed acquire static charge.

Opt. Prop. R.I. high, $\alpha = 1.652$, $\beta = 1.655$, $\gamma = 1.671$. Birefringence moderate, $\gamma - \alpha = 0.019$. Optically biaxial, positive. Optic axial plane $\parallel (010)$. $Bxa \rightarrow Z$ makes angle of 41° with c axis in obtuse angle β . Oblique extinction, either about 40° or 10° if measured from (101) traces in (010) . $2V = 50^\circ \pm$; $2E = 88^\circ 40'$. Moderate dispersion, $\rho > \nu$. $Y = b$. Occasionally pleochroic but orientation of colours varies with different specimens.

Characters in Sediments. Green, blue prismatic, water-worn grains, irregular outline and often fractured in alluvial specimens. Brown, opaque 'mushroom' or 'fungi-form' pellets are described from British Guiana (L. J. Spencer).

Occurrence. In auriferous gravels, R. Sanarka, S. Urals, U.S.S.R.¹; in alluvials at Bahia and Minas Geraes, Brazil²; in diamond washings in British Guiana³.

Possible Sources of Derivation. Chlorite schist and associated crystalline metamorphic rocks; pegmatite.

REMARKS.—A rare mineral, to be anticipated in environments containing other beryllium species, often associated with diamonds, especially topaz, occasionally gold and platinum. Confirm spectrographically.

References

^{1, 2, 3} C. Raeburn and H. B. Milner, *Alluvial Prospecting*, (Murby, London), 1927, p. 384.

General References

J. C. Branner, *Amer. Journ. Sci.*, **31**, 1911, p. 480.

L. J. Spencer, Euclase and Platinum from Diamond-Washings in British Guiana, *Miner. Mag.*, **20**, 1924, p. 186 and refs. cited.

EUDIALITE

Chem. Comp. $4[\text{Na}_4(\text{Ca}, \text{Fe})_2\text{ZrSi}_6\text{O}_{17}(\text{OH}, \text{Cl})_2]$, Eudialite; $4[(\text{Ca}, \text{Na}, \text{Ce})_3(\text{Zr}, \text{Fe})_2\text{Si}_6(\text{O}, \text{OH}, \text{Cl})_2\text{O}]$, (Eucolite).

System. Trigonal.

Habit. Varied.

Structure. Crystalline, often zoned.

Cleavage. Distinct, $\parallel (0001)$; poor $\parallel (10\bar{2}0)$.

Fracture. Irregular.

Hardness. 5–6.

Spec. Grav. 2.8–3.1.

Lustre. Vitreous.

Colour. Pink, red, brown.

Mag. Prop. Non-magnetic.

Elect. Prop. —

Opt. Prop. R.I. high, $\omega = 1.610$, $\epsilon = 1.611$. Birefringence weak, $\epsilon - \omega = 0.001$. Optically uniaxial positive. Pleochroism weak. Absorption $\omega > \epsilon$. May be optically anomalous if the cerium component (eucolite) is prominent.

Characters in Sediments. Pink to red, flattened grains, usually revealing cleavage traces.

Occurrence. In recent deposits; shore sands, S. Coast Greenland¹.

Possible Sources of Derivation. Nepheline syenite, soda-bearing granite.

REMARKS.—An extremely rare detrital mineral, to be anticipated only where alkaline igneous rocks are locally laid under contribution. The above chemical formulae are uncertain.

References

¹ R. D. Crommelin, *Meddelelser om Grønland*, **113**, 1937.

General References

E. Kostyleva, *N. Jahrb. Min.*, **1**, 1931, p. 363.

A. Lacroix, *Bull. Soc. Fr. Min.*, **38**, 1915, p. 278; also *Minéral Madagascar*, **1**, 1922, p. 588.

FAYALITE

(OLIVINE GROUP)

Chem. Comp. $2\text{FeO}, \text{SiO}_2$.*System.* Orthorhombic.*Habit.* Prismatic, tabular \parallel (100). Twinning rare on (011).*Structure.* Crystalline.*Cleavage.* Distinct \parallel (010), indifferent \parallel (100).*Fracture.* Irregular.*Hardness.* 6.5.*Spec. Grav.* 4.3.*Lustre.* Vitreous.*Colour.* Pale greenish yellow. Transparent to translucent.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. very high, $\alpha = 1.835$, $\beta = 1.877$, $\gamma = 1.886$. Birefringence strong, $\gamma - \alpha = 0.051$. Interference tints sometimes abnormal 'blues and yellows'. Optically biaxial, negative. Optical axial plane \parallel (001). $Bxa = \perp$ (010) = b. $Z = a$. Straight extinction \parallel prism and principal cleavage. $2V = 47^\circ - 50^\circ$. Dispersion strong, $\rho > \nu$. Weakly pleochroic in some examples, $Y = \text{orange yellow} > X = \text{greenish yellow} > Z = \text{greenish yellow}$.*Characters in Sediments.* Detrital fayalite is rare in sediments. It tends to the general irregular form of grain characteristic of olivine, but possesses stronger relief (higher R.I.), stronger birefringence (especially when abnormal blue and yellow tints are revealed) than does that species. Alteration to hematite, limonite or goethite along cleavage lines is noted, less commonly to antigorite (p. 46) when magnesium is present.*Occurrence.* In Pennsylvanian and Devonian Sandstones, Mid-Continent, U.S.A.¹; in shore sand, S. Coast Greenland².*Possible Sources of Derivation.* Volcanic rocks, certain pegmatites; metallurgical slag.*References*¹ F. C. Edson, *Rep. Cmmtte. Sedimentation* 1928-29, No. 92, National Research Council, U.S.A., 1930, p. 70.² R. D. Crommelin, *Meddelelser om Grønland*, 113, 1937.

FLINT

(See Chalcedony, p. 73)

FLUORITE

[Pl. 23A, B, between pp. 112-113]

Chem. Comp. CaF_2 .*System.* Isometric.*Habit.* Either simple or modified cube; octahedral, dodecahedral; interpenetrant twins common about (111).

Structure. Crystalline, compact, massive.

Cleavage. Perfect \parallel (111).

Fracture. Conchoidal.

Hardness. 4.

Spec. Grav. 3.18.

Lustre. Vitreous.

Colour. Commonly colourless, white, green, blue or purple; also pink, brown and intermediate shades. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low. $n = 1.434$. Optically isotropic. May show anomalous polarization due to internal strain.

Characters in Sediments. Frequently occurs as octahedral cleavage fragments, subangular or irregular. Rounded grains rare. Triangular plates with modified edges sometimes found. Detrital grains of this mineral are often violet in colour, though the colouring matter may not permeate the whole grain, thus rendering it 'blotchy'. Inclusions of iron-ores, manganese, hydrocarbon (?) or fluid. Diagnosed by its octahedral tendency, prominent relief and lower R.I. than Canada balsam, also by its isotropism.

Occurrence. In the Old Red Sandstone, Cardiff¹; in the Carboniferous Limestone, Matlock district, Derbyshire (see p. 523)²; in the Lower Carboniferous Sandstone, Cumberland³; in the Bunter Pebble Bed, West of England⁴; in the New Red Sandstone, West of England⁵; in Dartmoor detritals⁶; in shore sand, St. Ives Bay, Cornwall⁷; in Red River sand, Camborne, Cornwall⁸; prolific in shore sand at Down-derry, near Looe, Cornwall⁸.

Later Records. In Lower Permian, S. Durham⁹; in Permo-Triassic, Elgin Sandstone, Greenbrae, Cummingstown, Scotland¹⁰; in Beach sand, Carbis Bay, Cornwall¹¹.

Possible Sources of Derivation. Acid igneous rocks, metamorphic rocks and metalliferous veins. Also limestones.

References

¹ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **35**, 1924, p. 489.

² Author's observations.

³ H. P. Lewis, *Geol. Mag.*, **68**, 1931, p. 543.

⁴ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 620.

⁵ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 231.

⁶ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 37.

⁷ T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 122.

⁸ Author's observations.

⁹ A. Fowler, *Geol. Mag.*, **80**, 1943, p. 41.

¹⁰ K. C. Dunham and ors., *Mem. Geol. Surv., Min. Res. Gt. Brit.*, **4**, 1952, p. 14.

¹¹ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General Reference

J. Drugman, Different Habits of Fluorite Crystals, *Miner. Mag.*, **23**, 1932, p. 137.

FUCHSITE

(MICA GROUP)

Chem. Comp. Chromium mica, Cr_2O_3 replacing part Al_2O_3 .*System.* Monoclinic.*Habit.* Platy || (001).*Structure.* Crystalline, laminated.*Cleavage.* Perfect || (001).*Fracture.* Irregular.*Hardness.* 2.5.*Spec. Grav.* 2.86.*Lustre.* Pearly.*Colour.* Green Translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. low, $\beta = 1.594$. Birefringence strong, $\gamma - \alpha = 0.04$.

Optically biaxial, negative. $Bxa = X \parallel c$. $2V = 40^\circ$. $2E = 66^\circ$. Basal cleavage plates yield good biaxial interference figure. Dispersion strong, $\rho > \nu$. Pleochroism, noted in thick grains, $X =$ colourless or pale blue, $Y =$ yellowish green, $Z =$ dark bluish green.

Characters in Sediments. Fuchsite, the chromium mica, is rare in sediments, but where diagnosed is distinguished by its micaceous habit, green colour and pleochroism.

Occurrence. At the base of the San Onofre Breccia (Lower Miocene), California, U.S.A.¹; in soils from Western Australia².

Possible Sources of Derivation. Micaceous quartzite; mica schist; less commonly in gneiss and dolomite.

References

¹ A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, **15**, 1925, p. 159.

² D. Carroll, *Geol. Mag.*, **73**, 1936, p. 503.

GADOLINITE

Chem. Comp. $2[\text{Be}_2\text{FeY}_2\text{Si}_2\text{O}_{10}]$ with other rare earths replacing Y.*System.* Monoclinic.*Habit.* Prismatic, usually with basal terminations.*Structure.* Crystalline, coarse granular.*Cleavage.* None.*Fracture.* Conchoidal, splintery; brittle.*Hardness.* 6.5-7.*Spec. Grav.* 4-4.5.*Lustre.* Vitreous, resinous.*Colour.* Greenish-black, brown. Translucent to opaque.*Mag. Prop.* Slightly magnetic; depends on amount of iron.*Elect. Prop.* Poor conductor.

Opt. Prop. R.I. high, variable; $\alpha = 1.78$, $\beta = 1.78 \pm$, $\gamma = 1.785$ (Larsen). Birefringence weak, $\gamma - \alpha = 0.005$, but varies even in the same specimen: in some cases isotropic. Optically biaxial, positive.

Optic axial plane \parallel (010). $Bxa = Z$ makes angle of 4° – 8° with c in greenish varieties, 12° – 15° in darker varieties, both in acute angle β . Strong dispersion $\rho > \nu$. $2V = 85^{\circ}$. Oblique extinction, small angle. Non-pleochroic in small crystals but in large dark-coloured specimens may be $X =$ olive green, $Y = Z =$ grass green (Winchell).

Characters in Sediments. Greenish-brown, water-worn prismatic grains.

Occurrence. Has been recorded from Newcastle, Mourne Mts., Ireland¹; also from Llano Co., Texas, U.S.A.².

Possible Sources of Derivation. Granite: pegmatite.

REMARKS.—Extremely rare but to be anticipated locally in deposits derived from certain granites and pegmatites from which it has been recorded and studied. Chemical and spectrographic confirmatory tests should be made.

References

¹ J. D. and E. S. Dana, *System of Mineralogy*, 6th ed., (Kegan Paul, Trench, Trübner, London), 1892, p. 511.

² *Ibid.*, p. 512.

GALENA

Chem. Comp. PbS.

System. Isometric.

Habit. Cube, octahedron or combination of both.

Structure. Crystalline or massive.

Cleavage. Perfect \parallel (100).

Fracture. Even.

Hardness. 2.5–2.75.

Spec. Grav. 7.4–7.6.

Lustre. Metallic.

Colour. Lead-grey. Opaque. Grey to white in vertical reflected light.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Characters in Sediments. Detrital galena is characterized by its colour, lustre, cubic form (usually cleavage) or by its occurrence as small, shapeless particles of typical lead-grey metallic lustre. With large

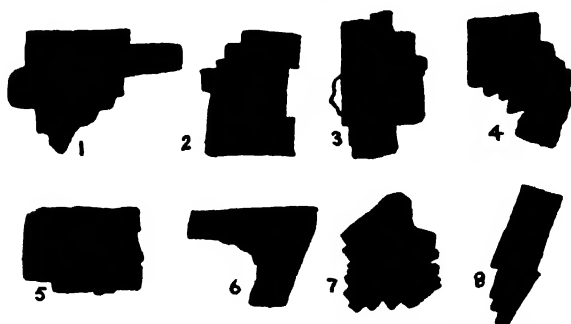


FIG. 39. Galena from Triassic Sandstone, Alderley Edge, Cheshire [$\times 50$]

grains, a black or blue superficial tarnish or white, powdery encrustation (cerussite, PbCO_3) may be noted. It is not a common constituent of sediments unless authigenic or locally where sulphide veins have contributed to sedimentary deposits.

Occurrence. Old Red Sandstone beneath London (Richmond boring, 1882)¹; in the Triassic Sandstones of Alderley Edge, Cheshire²; in the Fuller's earth (Aptian) of Redhill, Surrey³; also of Nutfield, Surrey⁴.

Later Records. In Magnesian Limestone, S. Durham⁵; in Fuller's Earth, Surrey⁶.

Possible Sources of Derivation. Veins and beds in limestones; metallic sulphides with quartz or other gangue material; silver-lead ores; rarely in gneiss, granite-pegmatite etc.

References

¹ J. W. Judd, *Quart. Journ. Geol. Soc.*, **40**, 1884, p. 749.

² Author's observation. (N.B.—Much of this material is clearly an impregnation product, i.e. authigenic.) See also A. Holmes, *Petrographic Methods*, (Murby, London), 1921, p. 191.

³ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, p. 86.

⁴ E. F. Newton, *Proc. Geol. Assoc.*, **48**, 1937, p. 181.

⁵ A. Fowler, *Proc. Geol. Assoc.*, **67**, 1956, p. 256.

⁶ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

GARNET

See varieties:

Almandite (p. 34).

Andradite (p. 41).

Grossularite (p. 117).

Melanite (p. 142).

Pyrope (p. 169).

Spessartite (p. 181).

Uvarovite (p. 199).

GASTALDITE

(See Glaucophane, p. 113)

GIBBSITE (HYDRARGILLITE)

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Hexagonal basal tablets, lamellar.

Structure. Crystalline, massive, concretionary.

Cleavage. Perfect \parallel (001) giving laminae-like mica.

Fracture. Uneven.

Hardness. 3.

Spec. Grav. 2.35.

Lustre. Porcellaneous, dull.

Colour. White, grey, green. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.566$, $\beta = 1.566$, $\gamma = 1.587$. Birefringence moderate, $\gamma - \alpha = 0.021$. Optically biaxial, positive. Optic axial plane

$\perp(001)$. $Bxa = Z$ inclined at 21° – 44° to c ; Y or $X = b$. $2V = 0^{\circ}$ – 40° (variable). Dispersion strong, $\rho > \nu$ or $\rho < \nu$. Non-pleochroic.

Characters in Sediments. Occurs as tabular grains of pseudo-hexagonal shape flattened $\parallel(001)$ or in irregular forms. It is probably authigenic in most instances in sediments. Liable to confusion with kaolinite (p. 130) and muscovite (p. 148); it has a higher birefringence than the former and a different sign from the latter.

Occurrence. In the Karstland bauxite¹; in the residual clays of the Eastern United States².

Later Records. In Bauxite deposits, Co. Antrim³.

Possible Sources of Derivation. Bauxite deposits. Felspar (by decomposition).

References

¹ M. Kispatic, *N.J.f. Min.*, B.-Bd., **34**, 1912, p. 513.

² H. Ries, W. S. Bailey and ors., *U.S. Geol. Surv., Bull.*, 708, 1922.

³ V. A. Eyles, F. A. Bannister, G. W. Brindley and J. Goodyear, *Mem. Geol. Surv.*, 1952, p. 39.

GLAUCONITE*

[Pl. 23C, between pp. 112–113]

Chem. Comp. SiO_2 , Al_2O_3 , Fe_2O_3 , FeO , MgO , K_2O , H_2O ;
 $KMg(Fe, Al)_3Si_8O_{18} \cdot 3H_2O$ (*A. N. Winchell*).

System. Monoclinic.

Habit. Microcrystalline, laminated, platy; appears amorphous.

Structure. Granular, irregular. Organic structures common.

Cleavage. Perfect $\parallel(001)$.

Fracture. Uneven.

Hardness. 2.

Spec. Grav. 2.2–2.8.

Lustre. Dull, sometimes vitreous.

Colour. Various shades of green, olive green, blackish green, blackish yellow. Brown when altered. Translucent.

Mag. Prop. Moderately magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, variable: $\alpha = 1.590$ – 1.612 , $\beta = 1.609$ – 1.643 , $\gamma = 1.610$ – 1.644 (*A. N. Winchell* quoting *C. S. Ross*). Birefringence moderate, $\gamma - \alpha = 0.020$ – 0.032 . Optically biaxial, negative. $Bxa = X$ nearly $\perp(001)$ cleavage. $2V = 0^{\circ}$ – 20° . $2E = 33^{\circ} \pm$. Dispersion $\rho > \nu$. Pleochroism: $X =$ straw yellow or pale yellow green $< Y = Z =$ green to yellowish green; or $X =$ dark bluish green, Y and $Z =$ lemon yellow.

Characters in Sediments. Rounded or irregular grains or aggregates, usually characteristic of the 'light' material of certain sediments. Under high power magnification and with polarized light, distinct optical properties (as above) may be discerned. Frequently occurs as casts of *foraminifera*. Commonly dark green in colour, if not altogether opaque; strong tendency to show decomposition to limonite.

* See also Ch. III, p. 319.

Occurrence. In the Cambrian, Ordovician, Silurian, Old Red Sandstone of the Midlands¹; in the Upper Lias-Lower Inferior Oolite of the West of England²; Lower Greensand (especially the Sandgate Beds) of the Weald³; in the Gault, Upper Greensand and Lower Chalk of Surrey⁴; in the Upper Greensand of the Weymouth district, Dorset⁵; in the Greensand of the Haldon Hills, Devonshire⁶; in the Thanet Beds, Reading Beds and London Clay of the N.E. part of the London Basin⁷; detrital glauconite in the Oligocene beds of Bovey Tracey, Devonshire⁸; in the Bagshot Beds of Essex⁹; in the Pliocene deposits of West Cornwall¹⁰; in the later Tertiary deposits of the East of England¹¹; in various valley gravels and loams of Surrey and the London district¹².

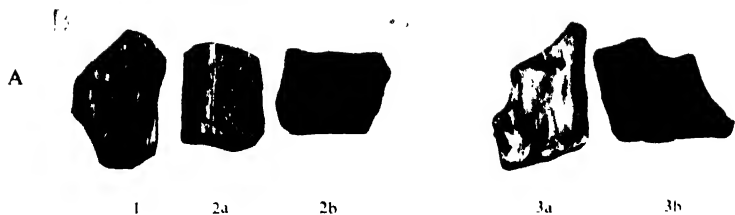
Later Records. In Lower Greensand, W. Weald¹³; in Reading Beds, Reading¹⁴; in Bracklesham Beds, London Basin¹⁵.

Possible Sources of Derivation. Sedimentary rocks, more rarely from amygdaloidal lavas. Frequently of organic origin.

REMARKS.—Glauconite is a mineral of considerable mineralogical and geological interest. It was for a long time supposed to be amorphous, but recent researches have shown this view to be untenable, since the 'amorphous' granules so often described from sediments have in many cases been proved to be made up of laminae having specific optical properties referable to monoclinic crystals. Glauconite occurs in abundance at certain stratigraphical horizons, especially in the Cretaceous Greensands. Its properties vary largely with amount of iron present, this factor affecting the S.G., which in some cases is > 2.80 . Most varieties are decomposed by HCl, hence in preliminary treatment of samples with this acid much of the glauconite may be lost. Its prolific occurrence in the Greensands would seem to be a function of its chemical stability in this instance, rather than of accentuated development at that epoch. There is no reason to suppose that it was initially less common in older than in younger sediments; on the contrary, its characters frequently suggest derivation and redeposition from pre-existing deposits.* (See particularly p. 443 of this volume, references there cited, also paper by A. F. Hallimond (below).)

References

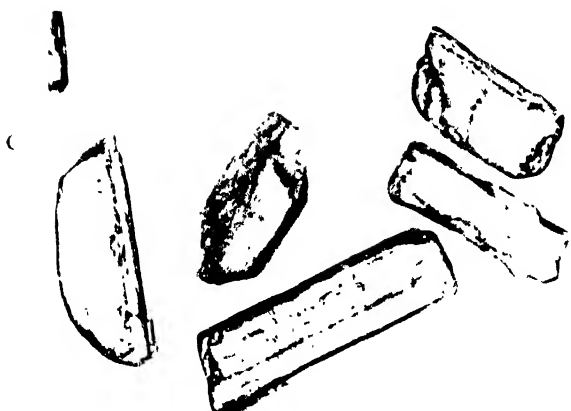
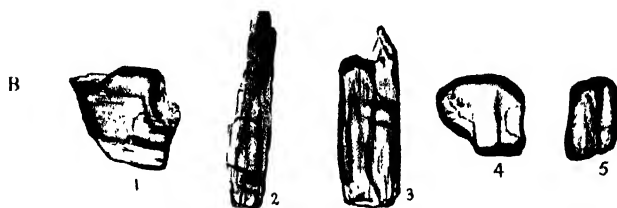
- ¹ W. F. Fleet, *Geol. Mag.*, **62**, 1925, pp. 101, 102, 104, 106, 126.
- ² P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, pp. 257, 258, 262.
- ^{3, 4} G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, pp. 82, 92.
- ⁵ Author's observations.
- ⁶ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, pp. 209, 226.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1915, table iv and pp. 557, 580.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, pp. 218, 220.
- ⁹ S. W. Wooldridge, *Proc. Geol. Assoc.*, **35**, 1924, pp. 364, 376.
- ¹⁰ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 348.
- ¹¹ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 342.
- ¹² G. M. Davies, *loc. cit.*, p. 78.
- ¹³ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
- ¹⁴ P. S. Walder, *Proc. Geol. Assoc.*, **51**, 1940, p. 215.
- ¹⁵ K. P. Oakley, *Geol. Surv. Gt. Brit., Wartime Pamphlet* **33**, 1943.



A DU'MORTII RITI

- 1 Blue prismatic grain with vertical striations. Bridport Sand, West Bay, Dorset. [x 130]
- 2 Upper Greensand, Lulworth Cove, Dorset. [x 105] (a) Position of minimum absorption
(b) Position of maximum absorption
- 3 Bagshot Beds. 3 mls. W. of Ringwood, Hants. [x 130] (a) and (b) as in 2 above

[1-3 Photos by A. W. GROVES]



B, C ENSTATITI

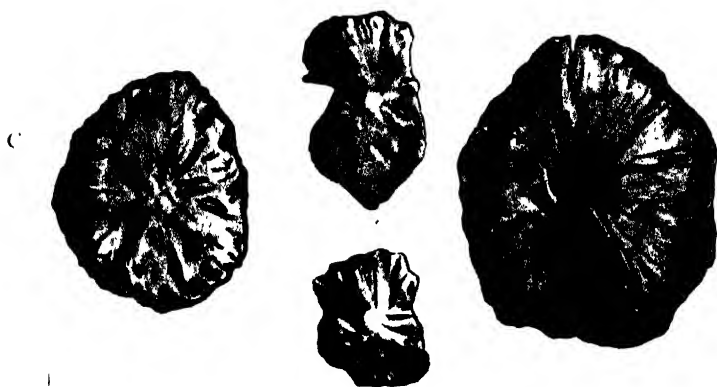
- B 1-3 Shore Sand, Kynance, Cornwall. [x 40]
- B 4 Shore Sand, Speeton, Yorkshire. [x 40]
- B 5 Blown Sand, Newgale, Pembrokeshire. [x 40]
- C Shore Sand, Cornwall. [x 48]



A, B EPIDOTE.

A Tocene Virginia, U.S.A. [x 38]

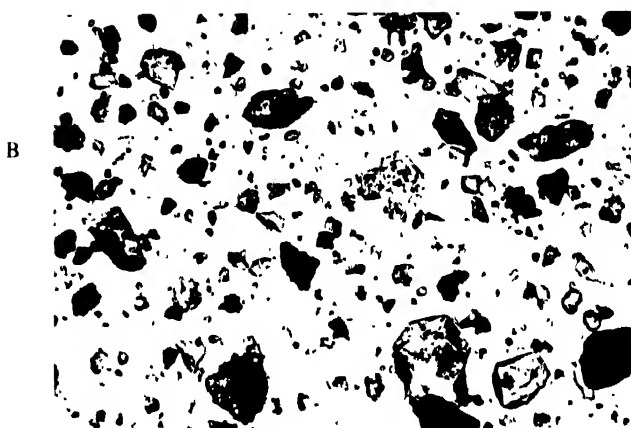
B Shore Sand Galway [x 62]



C. FUCHSIT.

Kanetour Gorge, Potaro River, Tributary of Essequibo, British Guiana [x 3]

(After L. J. Spencer, *Miner. Mag.*, 20, 1924 p. 190.)



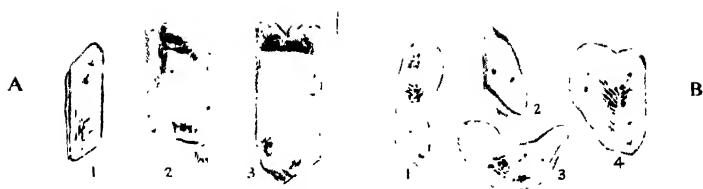
A. B FLUORITE

A. 1-4 Red River Sand, Cornwall [x 40]
 B Carboniferous Limestone, Matlock, Derbyshire [x 64]



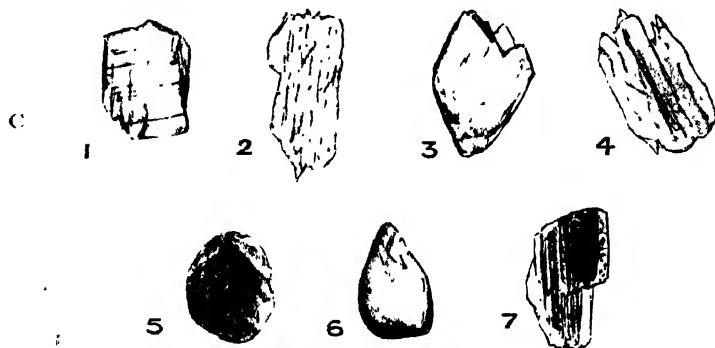
C. GLAUCONITI

Casts of *Foraminifera*, Upper Greensand, Chaldon Herring, Dorset [x 50]



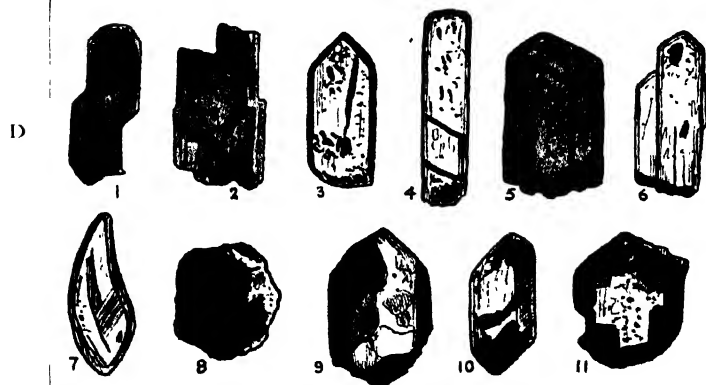
A, B. GYPSUM.

- A 1 3 Recent Sand, Bulawayo, Rhodesia [x 30]
 B 1 4 London Clay, Thornton Heath, Surrey [x 40]
 N.B. B 1, 3 and 4 are twinned on (100) (From brush-drawings by F. Smithson)



C. GLAUCOPHANE AND HORNBLENDI

- C 1 3 Glaucophane from Miocene Sands, Trinidad [x 70]
 C 2, 4 Hornblende from Miocene Sands, Trinidad [x 70]
 C 5 Glaucophane from Blown Sands, Newgale, Pembrokeshire [x 70]
 C 6 Glaucophane from Glacial Sands, Withybush, Haverfordwest, Pembrokeshire [x 40]
 C 7 Hornblende from Blown Sands, Newgale, Pembrokeshire [x 70]



D. HYPERSTHENE.

- D 1 3 Sand from Fiji [x 25]
 D 4 6 Volcanic Sand, Mont Pelee, Martinique [x 25]
 D 7 Shore Sand, S.E. Arabia [x 25]
 D 8 Recent Sand, Gold Coast, W. Africa [x 25]
 D 9 12 Pleistocene Sand, Portugal [x 25]

General References

- *P. G. H. Boswell, *The Application of Petrographical and Quantitative Methods to Stratigraphy*, *Geol. Mag.*, 1916, pp. 107, etc.
 A. F. Hallimond, *Miner. Mag.*, 19, 1922, p. 330.
 F. W. Clark, *The Data of Geochemistry*, *U.S. Geol. Surv., Bull.* 770, 1924, pp. 137, 510, 584.
 H. Schneider, *Journ. Geol.*, 35, 1927, p. 289.
 C. S. Ross, *U.S. National Mus. Proc.*, 19, 1926, No. 2.
 E. W. Galliher, *Glaucophane Genesis*, *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1351.

GLAUCOPHANE

(AMPHIBOLE GROUP)

[Pl. 24C, between pp. 112–113]

Chem. Comp. $\text{Na}_2\text{O} \cdot (\text{Fe}, \text{Ca}, \text{Mg})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ *System.* Monoclinic.*Habit.* Prismatic, short 'stumpy' crystals.*Structure.* Crystalline.*Cleavage.* Perfect \parallel (110).*Fracture.* Uneven.*Hardness.* 6.*Spec. Grav.* 3–3.15.*Lustre.* Vitreous, pearly on cleavage fragments.*Colour.* Colourless, pale blue, lavender blue to bluish-black.*Mag. Prop.* Moderately magnetic.*Elect. Prop.* Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.621$, $\beta = 1.638$, $\gamma = 1.638$. Birefringence moderate, $\gamma - \alpha = 0.017$. Optically biaxial, negative. Optic axial plane \parallel (010). $Bxa = X$. $Y \parallel b$, $Z \wedge c = 5^\circ \pm$. Oblique extinction, $3^\circ - 11^\circ$, rarely $16^\circ - 22^\circ$ in partially altered forms. Sometimes fails to extinguish in any position. Length and cleavage direction slow. $2V = 45^\circ \pm$. $2E = 77^\circ$. Pleochroism very marked, $Z = \text{blue}$, $Y = \text{lavender or violet}$, $X = \text{colourless to yellow or yellow-green}$. Dispersion strong, $\rho > \nu$.

Characters in Sediments. Commonly occurs as irregular grains with tendency to elongation in direction of the principal crystallographic axis (prismatic) and may or may not exhibit the characteristic pleochroism by which this species is invariably diagnosed. Many grains are undoubtedly derived by (110) cleavage. Another type is ragged in appearance, not unlike some varieties of tremolite or (save the colour) actinolite. Striae \parallel principal axis occasionally observed. Inclusions are usually common, e.g. magnetite, rutile, ? titanite, apatite.

Occurrence. In the Upper Lias—Lower Inferior Oolite of the West of England¹; in the Northampton Ironstone²; in Lias—Inferior Oolite of the Midlands³; in the Kimmeridgian-Portlandian sands of the South of England⁴; in the Ashdown Sand (Wealden) of Hastings, Sussex⁵; in the Oldhaven and Reading Beds of the London Basin⁶; in Glacial Deposits of East Anglia⁷; in wind-blown deposits of Guernsey⁸; in blown sands from Newgale, Pembrokeshire⁹; in sands

of preglacial screes in Anglesey¹⁰; also shore sands of that island¹¹; in valley deposits in Surrey¹².

Possible Sources of Derivation. Metamorphic rocks, especially schistose types; eclogites. Crystalline limestones.

REMARKS.—The more thorough searching of sediments in recent years has brought to light the widespread occurrence of this interesting mineral and, although seldom common in any one deposit, it has been shown by different investigators to occur consistently at certain horizons over large areas. In the author's experience it is especially prevalent in Miocene sediments (a coincidence) in countries as far removed as Trinidad, Venezuela, California, Italy and Iraq. In this respect it achieves the same distinction that andalusite has in connexion with its occurrence in Pliocene deposits (p. 40). P. G. H. Boswell remarks on the frequent association of glaucophane and chloritoid³. It is liable to be confused with *crossite*: see p. 91.

Closely related to glaucophane is '*gastaldite*', an anhydrous, soda-bearing amphibole, having similar properties to glaucophane, but distinguished by its stronger birefringence and weaker dispersion.

Records of *gastaldite* are as follows:—in the Miocene sandstones of central Italy¹³; in sea bed deposits in an area ranging from Corsica and Sardinia to Sicily¹⁴; in the Ravenna sands, Italy¹⁵; in the sand of Sansego, a small island off Quarnero¹⁶.

References

- ¹ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 256.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 383.
- ³ P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, **18**, 1926–27, p. 139.
- ⁴ E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 250.
- ⁵ H. B. Milner, *Proc. Geol. Assoc.*, **36**, 1925, p. 315.
- ^{6-8, 10, 12} P. G. H. Boswell, *loc. cit.* (1926–27).
- ^{9, 11} Author's observations.
- ¹³ I. Chelussi, *Boll. Soc. geol. ital.*, **27**, 1908, p. 251.
- ¹⁴ F. Salmoiraghi, *Rend. R. Ist. lomb.*, **43**, 1910, p. 432.
- ¹⁵ I. Chelussi, *Boll. Soc. geol. ital.*, **30**, 1911, p. 183.
- ¹⁶ F. Salmoiraghi, *Rend. R. Ist. lomb.*, **40**, 1907, p. 870.

GOETHITE

Chem. Comp. $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O} + n\text{H}_2\text{O}$.

System. Orthorhombic (in certain conditions tetragonal). Also amorphous.

Habit. Prisms with vertical striations; scaly or tabular || (010).

Structure. Crystalline, massive.

Cleavage. Perfect || (010).

Fracture. Irregular.

Hardness. 5–5.5.

Spec. Grav. 4.0–4.4.

Lustre. Submetallic, dull.

Colour. Brown, yellow, red.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 2.15$, $\beta = 2.22$, $\gamma = 2.224$. Birefringence strong, $\gamma - \alpha = 0.074$. Optically biaxial, negative. Optic orientation varies for light of different wave length, optic axial plane being (100) for red light and (001) for yellow light, etc. Uniaxial for light of wave length 610–620 m μ (*A. N. Winchell*). $Bxa \perp (010)$; prisms have positive elongation. Pleochroism variable (seen in thin section): X = clear yellow, Y = brownish yellow, Z = orange yellow. Strong dispersion.

Characters in Sediments. Detrital goethite is probably far more common in sediments than records indicate. The tendency to diagnose 'limonite' (p. 138) for most apparently amorphous brown grains common in many sandstones, for instance, would probably be checked on closer examination under high power. The essential difference between goethite and limonite is the crystal form and anisotropic character of the former, also its pleochroism seen in sufficiently thin, translucent grains. With dark ground illumination goethite grains appear grey and submetallic. Sometimes a fibrous tendency is observed which is possibly an intermediate stage in transformation to limonite.

Occurrence. Lower Carboniferous sandstone, West Cumberland¹.

Later Records. In Northampton Sand Ironstone, Northamptonshire²; in laterite deposits, Co. Antrim³; in Beach sand, Carbis Bay, Cornwall⁴.

Possible Sources of Derivation. Sedimentary iron ore deposits.

REMARKS.—In more massive iron ore deposits, much of the so-called 'limonite' is in reality goethite. Frequently an alteration product of pyrite (p. 167).

References

- ¹ H. P. Lewis, *Geol. Mag.*, **68**, 1931, p. 554.
- ² J. H. Taylor, *Mem. Geol. Surv.*, 1949, p. 2.
- ³ V. S. Eyles, F. A. Bannister, G. W. Brindley and J. Goodyear, *Mem. Geol. Surv., N. Ireland*, 1952, p. 40.
- ⁴ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 78.

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- E. Posnjak and H. E. Merwin, *Amer. Journ. Sci.*, **47**, 1919, p. 311.
V. A. Frank-Kamenetsky, *Doklady, Acad. Sci. U.S.S.R.*, **94**, 1954, p. 765.

GOLD

[Pl. 25, between pp. 128–129]

Chem. Comp. Pure gold, Au.

System. Isometric; hexoctahedral.

Habit. Octahedral, dodecahedral, cubic.

Structure. Crystalline; arborescent; dendritic; reticulated due to repeated twinning on (111).

Cleavage. None.

Fracture. Hackly.

Hardness. 2.5–3.

Spec. Grav. 19.3.

Lustre. Metallic.

Colour. Yellow, sometimes with silver tinge. Opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Good conductor.

Opt. Prop. In very thin flakes, translucent, isotropic.

Characters in Sediments. Rounded, flattened grains of distinctive colour and appearance.

Occurrence. In Dartmoor detritals¹.

Later Records. In Alluvial deposits, Perranwell Valley, Restronguet, Cornwall²; Tregoss Moor, St. Austell, Cornwall³; and Pentewan, St. Austell, Cornwall⁴.

Possible Sources of Derivation. Hydrothermal veins; quartzite; alluvial deposits.

REMARKS.—Authenticated records in British detrital sediments are rare. It is possible that in suitable environments the mineral may be overlooked in the heavy residues or in very small particles individually confused with pyrite. In suspected cases, confirmation may be sought by rubbing grains on a prepared mercury-covered chamois leather, when amalgamation takes place and the grains turn white.

References

¹ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 47.

² H. G. Dines, The Metalliferous Mining Region of South-West England, *Mem. Geol. Surv.*, 1, 1956, p. 274.

³ *Op cit.*, 2, p. 511.

⁴ *Op cit.*, 2, p. 568.

General Reference

A. Brammall, Gold and Silver in the Dartmoor Granite, *Miner. Mag.*, 21, 1926, p. 14.

GRAPHITE

Chem. Comp. Carbon, sometimes with iron and silica.

System. Trigonal.

Habit. Tabular (six-sided) plates or lamellae, often rounded; sometimes striated || trace of unit rhombohedron (10 $\bar{1}$ 1).

Structure. Crystalline, columnar, radiate, granular, compact, earthy.

Cleavage. Perfect || (0001); indistinct || (10 $\bar{1}$ 1).

Fracture. Irregular.

Hardness. 1-2.

Spec. Grav. 2.25.

Lustre. Metallic, sometimes dull, 'soot-black'.

Colour. Steel-grey to 'soot-black'. Opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $n = 2.0 \pm$. Normally opaque. In extremely thin flakes, translucent and transmits greenish light; such flakes are uniaxial negative.

Characters in Sediments. Occurs in the form of rounded, platy or irregular dull black grains, recognized chiefly by their appearance in reflected light.

Occurrence. In Devonian limestones of the Torquay district ('Carbon')¹; shore sands of the coast of North Cornwall²; beach sands of Florida, U.S.A.^{3,4}.

Possible Sources of Derivation. Metamorphic rocks: gneisses, phyllites, schists, altered limestones, quartzites.

REMARKS.—Detrital graphite is essentially a local species, hardly to be expected in ordinary sediments unless graphite-rich rocks have been laid under contribution to them. Certain shore sands lying close to phyllites which have undergone disintegration yield both free and composite grains of graphite, in the latter case associated generally with quartz.

References

¹ W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 150.

² Author's observations. See also P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, **13**, 1923, p. 268.

³ J. H. C. Martens, *19th Ann. Rep. Florida Geol. Surv.*, 1928, p. 154.

⁴ J. H. C. Martens, *Bull. Geol. Soc. Amer.*, **46**, 1935, p. 1580.

GROSSULARITE

(GARNET GROUP)

Chem. Comp. $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$.

System. Isometric.

Habit. Dodecahedral (110); trapezohedral (211) often modified by hexoctahedral faces. Striations often || (110).

Structure. Crystalline.

Cleavage. None.

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.4–3.6.

Lustre. Vitreous.

Colour. Yellow, brown, green, colourless. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $n = 1.735$. Optically isotropic. Often optically anomalous due to strain (?twinning), when crystals exhibit weak birefringence, biaxial negative characters and large optic axial angle. Such examples show strong dispersion but are non-pleochroic.

Characters in Sediments. Yellow-brown detrital grossularite is not a rare constituent of sediments derived from favourable contact-altered rocks such as metamorphosed limestones and schists. Dodecahedral or more complex forms are found as rounded or subangular grains having characteristic 'garnet' features. Alteration to epidote, chlorite minerals and calcite may be noted. High relief, colour, form, fracture, absence of cleavage and normally isotropism unite to distinguish this species.

Occurrence. In Triassic gypseous deposits and dolomites near Jena, Germany¹; in the limestone soils of the East Indian Archipelago²; in river concentrates, Belgian Congo³.

Possible Sources of Derivation. Metamorphosed limestone; schist; nephelene-syenites.

References

- ¹ E. Kalkowsky, *Zeitschr. deutsch. geol. Gesellsch.*, **73**, 1922, p. 1.
- ² J. Van Baren, *Comm. Geol. Inst. Agric. Univ. Wageningen*, **14**, 1928.
- ³ H. Buttgenbach, *Ann. Soc. géol. Belg. Liège*, **46**, 1923, p. B.229.

GYPSUM (SELENITE)*

[Pl. 24A, B, between pp. 112-113]

Chem. Comp. $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Simple, tabular \parallel (010) or prismatic, elongated or acicular \parallel vertical axis *c*. Frequently twinned on (100), less commonly on (101).

Structure. Crystalline, fibrous, massive or granular.

Cleavage. Perfect \parallel (010), imperfect \parallel (100) and $\bar{1}11$.

Fracture. None. Glide planes may be developed \parallel $\bar{1}03$ and $\bar{3}09$.

Hardness. 1.5-2.

Spec. Grav. 2.32.

Lustre. Vitreous to dull; pearly on (010) faces.

Colour. Colourless, white, sometimes stained by impurity. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha \approx 1.520$, $\beta \approx 1.523$, $\gamma \approx 1.530$. Birefringence moderate, $\gamma - \alpha \approx 0.010$. Optically biaxial, positive. Optic axial plane \parallel (010). $Bxa : Z$ inclined at $37\frac{1}{2}^\circ$ to normal of (100) and makes the complementary angle of $52\frac{1}{2}^\circ$ with the *c* axis in the obtuse angle β . $Y \parallel b$. Fibres fast \parallel length. Optic axial angle large, $2E \approx 95^\circ$, $2V = 58^\circ$. (010) folia give extinction angles of 13° and 37° . Strong inclined dispersion, $\rho > \nu$. Optical properties vary considerably with temperature.

Characters in Sediments. Found as colourless, well formed crystals (selenite), often somewhat rounded; or as platy cleavage fragments of a pseudo-rhombohedral character and determined by (010) cleavage. Other developments noted include fibrous and matted types, spherulites and radiating clusters; these frequently show brush-polarization; twinned crystals, about (100), also occur, the plane of composition being represented by a sharply defined line from which the two halves of the crystal extinguish at an angle of $37\frac{1}{2}^\circ$. Twinned and corroded selenites have been described from the London Clay and are good examples of these developments⁶. The irregularly shaped grains and aggregates of gypsum (as distinct from the crystalline selenite) met with in sandstones, etc., are probably derived from the

* Selenite is the name used generally for crystalline varieties of the more common massive gypsum deposits.

disintegration of the mineral occurring in the form of a cementing medium; in this respect the grains resemble the haphazard forms of barite (*q.v.* p. 56) from which, however, they are readily distinguished by optical properties. Immature developments from anhydrite (*q.v.* p. 42) are common in some rocks; such grains have a higher S.G. than normal gypsum, also a higher R.I. than Canada balsam, though the characteristic properties of anhydrite, *e.g.* cleavage, form, are usually obscured. In the crystalline forms (selenite), zoning is often a feature, the zones being picked out by iron-ore inclusions; of the latter, rutile, apatite, hematite, magnetite are among those most commonly noted. Diagonal striae common. Selenite and gypsum are both diagnosed primarily by their low S.G. habit, colour and low R.I. (lower than Canada balsam), the crystalline variety, by very distinctive optical properties as noted above.

Occurrence. In the New Red Sandstone of the West of England¹; massive gypsum in the Triassic deposits of the Midlands, notably Nottinghamshire² and Leicestershire³; selenite in the Kimmeridge Clay, Shotover Hill, Oxford⁴; also in the Upper Kimmeridgian of Buckinghamshire⁵; in the London Clay of Thornton Heath, Surrey⁶; and at Harefield, Middlesex⁷. Many of the Miocene clays and marls of different countries yield beautiful varieties of selenite, *e.g.* the Naparima Marls, Trinidad, the Lower Fars of Iraq and Iran⁸; the latter countries famous also for their vast developments of massive gypsum.

Possible Sources of Derivation. Sedimentary rocks, saline deposits, from volcanic regions and metalliferous veins.

REMARKS.—There is good reason to believe that crystalline gypsum (selenite) occurs far more commonly in argillaceous rocks in the British Isles than the scanty records available would suggest. In washing out the light materials of such sediments, much of this gypsum may be lost or otherwise overlooked. It is certainly an interesting species and, like anhydrite, repays study, especially for the many and varied forms exhibited.

References

- ¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 231.
- ² W. H. Richardson, *Mineral Mag.*, **19**, 1921, p. 196.
- ³ T. O. Bosworth, *Keuper Marls around Charnwood, Leicester Lit. and Phil. Soc.*, 1913, ch. ix.
- ⁴ Well-known locality.
- ⁵ W. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 253.
- ⁶ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, p. 95.
- ^{7, 8} Author's observations.

HALLOYSITE*

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Isometric or amorphous.

Habit. White amorphous powder. Often colloidal.

Structure. Indefinite.

* See also Ch. III, p. 312.

Cleavage. None.

Fracture. ?

Hardness. 2.

Spec. Grav. 2.6.

Lustre. Earthy.

Colour. White.

Mag. Prop. Non-magnetic.

Elect. Prop. ?

Opt. Prop. R.I. low, $n = 1.47-1.57$ (increases on drying). Optically isotropic.

Characters in Sediments. Halloysite occurs in kaolinitic clays in which it has been identified in fine colloid fractions; also it occurs as beds and veins in certain ball clays, etc. Generally takes the form of white shapeless particles which are insoluble in acid and is identified by its R.I. (lower than Canada balsam) and powdery appearance. It is probably much commoner in sedimentary rocks than existing records indicate.

Occurrence. In clays from various stratigraphical horizons in the Cambrian, Carboniferous and Upper Cretaceous, U.S.A.¹; in clays of the Eastern United States²; in the Chalk, Worms Heath, Surrey³.

Possible Sources of Derivation. Ball clay, china clay, shale, Fuller's earth.

References

¹ R. E. Somers, *Journ. Washington Acad. Sci.*, 9, 1919, p. 113.

² H. Ries, W. S. Bayley and ors., *U.S. Geol. Surv. Bull.*, 708, 1922.

³ G. M. Davies, in W. Whitaker, *Quart. Journ. Geol. Soc.*, 75, 1920, p. 22.

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C. S. Ross and P. F. Kerr, Halloysite and Allophane, *U.S. Geol. Surv. Prof. Paper* 185-G, 1934.

R. E. Grim and R. H. Bray, The Mineral Constitution of Various Ceramic Clays, *Journ. Amer. Ceram. Soc.*, 19, 1936, p. 307.

R. E. Grim, *Clay Mineralogy*, (McGraw-Hill, New York), 1953.

HEMATITE

Chem. Comp. Fe_2O_3 .

System. Trigonal.

Habit. Euhedral; tabular $\parallel (0001)$; platy.

Structure. Crystalline, laminated, massive or earthy.

Cleavage. Doubtful. Parting $\parallel (0001)$ and $(10\bar{1}1)$, due to lamellar twinning.

Fracture. Subconchoidal, irregular.

Hardness. 5.

Spec. Grav. 5.2.

Lustre. Brilliant, metallic. Earthy varieties red.

Colour. Steel-grey. Translucent to opaque.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque in thick scales or grains. Translucent plates show

very high R.I., $\omega = 3.22$, $\epsilon = 2.94$ and extreme birefringence, $\omega - \epsilon = 0.28$; polarization tint often masked by natural colour. Optically uniaxial, negative. Pleochroic in sections \perp basal plane: $\omega =$ brownish red, $\epsilon =$ yellowish-red.

Characters in Sediments. Commonly found as irregular or rounded, earthy grains of a reddish-brown colour by reflected light, which is very characteristic. More rarely as rhombohedral grains or platy forms with splendid lustre. H. H. Thomas has described 'minute botryoidal grains, made up of spheroidal masses with radiate structure which give a black cross between crossed nicols'³.

Occurrence. In Devonian sediments of the Torquay district¹; in Permian rocks of the Torquay Promontory²; in the New Red Sandstone of the West of England³; in the Keuper Marls of Charnwood, Leicestershire⁴; in the Fairlight Clay (Wealden) of Sussex⁵; in the Thanet Beds, Reading Beds and London Clay of the N.E. part of the London Basin⁶; in the dune sands of South Wales⁷; in surface deposits of S.E. Devonshire⁸; in Dartmoor detritals⁹.

Later Records. In Downtonian, Tenbury, Worcestershire¹⁰; in St. Bees Sandstone, S. Cumberland and Furness¹¹; in laterite deposits, Co. Antrim¹²; in Beach Sand, Carbis Bay, Cornwall¹³.

Possible Sources of Derivation. Igneous and metamorphic rocks; metalliferous veins; limestones.

REMARKS.—Hematite occurs in sediments both as a primary and secondary constituent. In the latter case its partial alteration to limonite may frequently be observed. A common 'cementing' medium in sandstones.

References

- ¹ W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, pp. 140, etc.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, **38**, 1927, p. 134.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 232.
- ⁴ T. O. Bosworth, Keuper Marls around Charnwood, *Leicester Lit. and Phil. Soc.*, 1913, p. 94.
- ⁵ H. B. Milner, *Proc. Geol. Assoc.*, **36**, 1925, p. 315.
- ⁶ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1915, table iv, pp. 576, 578.
- ⁷ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 320.
- ⁸ W. G. Shannon, *Geol. Mag.*, **64**, 1927, pp. 146, 148.
- ⁹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 35.
- ¹⁰ P. S. Walder, *Proc. Geol. Assoc.*, **52**, 1941, p. 247.
- ¹¹ K. C. Dunham and W. C. C. Rose, *Proc. Geol. Assoc.*, **60**, 1949, p. 28.
- ¹² V. S. Eyles, F. A. Bannister, G. W. Brindley and J. Goodyear, *Mem. Geol. Surv.*, 1952, p. 40.
- ¹³ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 78.

HERCYNITE

(SPINEL GROUP)

Chem. Comp. FeO . Al₂O₃.

System. Isometric.

Habit. Octahedral, more commonly granular.

Structure. Fine granular, massive.

Cleavage. Imperfect \parallel (111).

Fracture. Uneven.

Hardness. 7.5.

Spec. Grav. 3.9.

Lustre. Vitreous, dull.

Colour. Black, blackish green. Translucent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Weak conductor.

Opt. Prop. R.I. very high, $n = 1.80 \pm$. Optically isotropic.

Characters in Sediments. On account of its dark colour hercynite is probably often overlooked in detrital sediments of relevant provenance. If grains are thin (at edges) a characteristic grass-green colour is noted. Otherwise as isolated grains, this species presents difficulties in positive diagnosis by microscopical means alone.

Occurrence. In the zirconiferous sandstone near Ashland, Virginia, U.S.A.¹.

Possible Sources of Derivation. Contact-altered rocks rich in alumina.

Reference

¹ T. L. Watson and F. L. Hess, *U.S. Geol. Surv., Bull.* 530, 1913, p. 165.

HEULANDITE

Chem. Comp. $[(Na, Ca)4-6Al_6(Al, Si)_4Si_{26}O_{72} \cdot 24H_2O]$.

System. Monoclinic.

Habit. Flattened \parallel (010); sometimes twinned about (100), globular, granular.

Structure. Crystalline.

Cleavage. Perfect \parallel (010).

Fracture. Subconchoidal, uneven; brittle.

Hardness. 3.5-4.

Spec. Grav. 2.18-2.22.

Lustre. Vitreous, pearly.

Colour. White, brown, grey, red. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. --

Opt. Prop. R.I. low, $\alpha = 1.498$, $\beta = 1.499$, $\gamma = 1.505$. Birefringence weak, $\gamma - \alpha = 0.007$. Optically biaxial, positive. Optic axial plane \perp (010). $Bxa \perp$ (010). Optic axial angle variable (as with other optical properties): $2V = 52^\circ$, $2E = 82^\circ$, $\rho > \nu$.

Characters in Sediments. Recorded as authigenic, in minute idiomorphic crystals and crusts attached to detrital sand grains (see reference ¹ below).

Occurrence. In Upper Miocene sandstone, Santa Cruz Co., California¹.

Possible Sources of Derivation. Basalt and basic volcanic detritus.

REMARKS.--A rare and localized species in sediments.

Reference

¹ C. M. Gilbert and M. G. McAndrews, *Journ. Sed. Pet.*, 18, 1948, p. 91.

General Reference

J. D. and E. S. Dana, *System of Mineralogy*, 6th ed. (Kegan Paul, Trench, Trübner, London), 1892, p. 574.

HIDDENITE

(VARIETY OF SPODUMENE, *q.v.* p. 184)

HORNBLLENDE

(AMPHIBOLE GROUP)

[Pl. 24C, *between pp.* 112–113]

Chem. Comp. $\text{Ca}_3\text{Na}_2(\text{Mg, Fe})_8(\text{Al, Fe})_4\text{Si}_{14}\text{O}_{44}(\text{OH})_4$.

System. Monoclinic.

Habit. Prismatic, elongated $\parallel c$.

Structure. Crystalline, tending to fibrous (actinolite, p. 29), massive.

Cleavage. Perfect $\parallel (110)$; less distinct $\parallel (100)$ and (010) . Cleavage traces in cross sections (\perp prism zone) intersect at angle of $124^\circ 11'$. Parting observed in twin crystals $\parallel (100)$, (010) and (001) .

Fracture. Uneven, subconchoidal. Frequently occurs at right angles to prismatic cleavage.

Hardness. 5–6.

Spec. Grav. 3–3.3, varying with composition.

Lustre. Vitreous.

Colour. Dark green, brown, black. Translucent.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.654$, $\beta = 1.666$, $\gamma = 1.670$. Birefringence moderate, $\gamma - \alpha = 0.016$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. $Bxa = X$ inclined at low angle to normal of (100) . Length and cleavage trace slow (positive). Oblique extinction. $Z \wedge c$ in (010) in obtuse angle β varies from 15° – 25° . $Y \parallel b$. Pleochroism varies, maximum absorption being in direction $\parallel Z$: $X =$ yellow or pale green $< Y =$ straw-yellow or yellow-green $< Z =$ brown or dark green. Dispersion, $\rho < \nu$.

Characters in Sediments. Green hornblende is most characteristic of detrital sediments, the brown type being rare (p. 445). Grains are usually in the form of elongated platy cleavage flakes determined by (110) and with frayed ends. (010) grains or cleavage flakes also noted. Prismatic striae are a feature of certain types. The colour may be unevenly distributed in the grain, being densest in the middle and becoming gradually paler towards the boundaries, especially the terminations, where the pleochroism is often best observed. Pleochroism is variable; some grains are non-pleochroic; most show weak colour-change, a few exhibiting strong properties in this respect, especially the soda-bearing types. The common pleochroism noted is the change from the pale colour (in the N.-S. position) to darker shades in the E.-W. position (the latter vibrations parallel to the short axis of the polarizer). Inclusions of magnetite, rutile, apatite and titanite have been observed in common hornblende, but they are not

particularly frequent. Alteration is mainly to chloritic matter and all stages of decomposition are detectable in detrital grains. Diagnosed chiefly by form, colour, marked prismatic cleavage, weak pleochroism and characteristic extinction angle.

Occurrence. In Devonian sediments of the Torquay district¹; in the Sandringham Sands, Snettisham Clay and Carstone (Lower Greensand) of Norfolk²; greenish-blue type in the Carstone of Hunstanton, Norfolk³; in the Red Chalk of Hunstanton⁴; in the Eocene and Oligocene deposits of the Haldon Hills and Bovey Tracey, Devonshire, respectively⁵; in the Thanet Beds and London Clay of the N.E. part of the London Basin⁶; in the Bagshot Beds of Essex⁷ and of N.W. London⁸; in the Pliocene sands of Bentley, Suffolk and Walton-on-Naze, Essex⁹; in the later Tertiary deposits of the East of England¹⁰; in the dune sands of South Wales (including barkevicite)¹¹; in glacial sands etc., of the Dublin district¹²; in shore sands of Guernsey¹³; in blown sands from Newgale, Pembrokeshire¹⁴.

Later Records. In St. Bees Sandstone, S. Cumberland and Furness¹⁵; in Lower Greensand, E. Kent¹⁶; in Beach Sand, Carbis Bay, Cornwall¹⁷.

Possible Sources of Derivation. Igneous and metamorphic rocks, especially granite, syenite, diorite and equivalent volcanic types and also hornblende schist, etc.

Note.—The closely allied members of the amphibole group are now described separately, as follows:

Actinolite (p. 29).	Gastaldite (p. 110).
Arfvedsonite (p. 50).	Glaucophane (p. 113).
Barkevicite (p. 58).	Riebeckite (p. 173).
Basaltine (p. 58).	Tremolite (p. 197).

References

- 1 W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 137.
- 2 H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, **20**, 1926, p. 350.
- 3 R. H. Rastall, *Geol. Mag.*, 1919, p. 214.
- 4 H. C. Versey and C. Carter, *loc. cit.*, p. 360.
- 5 P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- 6 P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1915, pp. 577, 580.
- 7 S. W. Wooldridge, *Proc. Geol. Assoc.*, **35**, 1924, p. 377.
- 8, 9 Author's observations.
- 10 I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 341.
- 11 A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 324.
- 12 F. Smithson, *Geol. Mag.*, **65**, 1928, p. 24.
- 13, 14 Author's observations.
- 15 K. C. Dunham and W. C. C. Rosé, *Proc. Geol. Assoc.*, **60**, 1949, p. 28.
- 16 G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- 17 C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

HUMITE

(HUMITE GROUP)

Chem. Comp. $6\text{MgO} \cdot 3\text{SiO}_2 \cdot \text{Mg}(\text{F}, \text{OH})_2$.

System. Orthorhombic.

Habit. Small, tabular (100) or (001).

Structure. Crystalline.

Cleavage. Perfect \parallel (001).

Fracture. Uneven.

Hardness. 6.

Spec. Grav. 3.1–3.3.

Lustre. Vitreous.

Colour. Colourless, white, yellow, brown. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.622$, $\beta = 1.632$, $\gamma = 1.652$. Birefringence strong, $\gamma - \alpha = 0.030$. Optically biaxial, positive. Optic axial plane \perp (010). $Bxa = Z \perp$ (010). Straight extinction \parallel cleavage trace in (010) sections. $X = a$, $Z = b$. $2V = 67^\circ - 70^\circ$. $2E = 132^\circ$. Dispersion weak, $\rho > \nu$. Pleochroism weak: $X =$ golden yellow $> Z =$ pale yellow, colourless $> Y =$ pale yellow or colourless.

Characters in Sediments. A comparatively rare mineral in sediments which should, however, be searched for where contact-altered dolomites have been laid under contribution. Occurs in tabular, golden yellow grains reminiscent of staurolite with which, doubtless, humite is often confused. It is to be noted that the golden yellow colour is $\parallel X$ in humite and to Z in staurolite and this serves as a primary distinguishing feature. In colourless grains, humite may be confused with olivine (p. 153). The latter has a higher R.I., optic axial plane \parallel (001) (perfect cleavage in humite, not in olivine) and not \perp (001) as in humite; olivine is seldom, if ever, pleochroic, but even colourless humite is likely to exhibit faint pleochroism.

Occurrence. In the sands from the outlets of subterranean rivers at Cerno and Zmiriac, in the bay of Buscari¹.

Possible Sources of Derivation. Contact-altered dolomitic limestone. Vein mineral.

REMARKS.—In doubtful cases, alleged humite should be tested for fluorine to distinguish from other magnesian silicates. Note chief allied species of this group (not as yet recorded in sediments):

Forsterite, $2MgO \cdot SiO_2$ (Orthorhombic).

Chondrodite, $4MgO \cdot Mg(F, OH)_2 \cdot 2SiO_2$ (Monoclinic).

Clinohumite, $8MgO \cdot Mg(F, OH)_2 \cdot 4SiO_2$ (Monoclinic).

Reference

- ¹ M. Kispatic, *Verh. k.-k. Geol. Reichsanst.*, 1910, p. 294.

HYALITE

(See Opal, p. 154)

HYPERSTHENE*

(PYROXENE GROUP)

[Pl. 24D, between pp. 112–113]

Chem. Comp. (Mg, Fe)O . SiO₂.*System.* Orthorhombic.*Habit.* Prismatic, bipyramidal, tabular || (100) or (010).*Structure.* Crystalline, lamellar, granular, massive.*Cleavage.* Distinct || (110), fair || (100) and (010).*Fracture.* Uneven.*Hardness.* 5–6.*Spec. Grav.* 3.3–3.5.*Lustre.* Vitreous, pearly on cleavage faces, submetallic, bronze-like (bronzite) on (010).*Colour.* Brownish-green, grey-green, olive, brown, yellow-brown. Translucent.*Mag. Prop.* Weakly magnetic, varies with iron content.*Elect. Prop.* Moderate conductor.*Opt. Prop.* R.I. high, $\alpha = 1.692$, $\beta = 1.702$, $\gamma = 1.705$. Birefringence moderate, $\gamma - \alpha = 0.013$. Optically biaxial, negative. Optic axial plane || (010). X || a, Y || b, Z || c. Straight extinction. $Bxa = X \perp (100)$. Optic axial angle varies with amount of FeO present. $2V = 75^\circ$ (decreases with increase of Fe). Dispersion weak, $\rho \div v$. Pleochroism marked in the more ferriiferous varieties: X – pink or red, Y – yellow, Z – green.*Characters in Sediments.* Not a common mineral in sediments as a rule, but to be anticipated in deposits derived from contiguous hypersthene-bearing igneous rocks. It usually assumes a ragged, prismatic habit (probably due to corrosion) and displays characteristic pleochroism, pink, red or brown to green (as above). Grains often full of minute inclusions (Schiller-structure), identified as iron-ore or some form of TiO₂. Detrital hypersthene is usually pale brownish-green to greyish-green in colour, though exceptionally deep brown euhedral varieties occur (with striking green pleochroism) in the vicinity of volcanic lavas. The (110) cleavage is often conspicuous.*Occurrence.* In the Silurian Rocks of Southern Scotland¹; 'Apart from Scottish occurrences, occasional pleochroic grains have been recorded from the Carboniferous of North Wales, the Permian of Lancashire, the Trias of the Vale of Clwyd, the Middle Lias, Portlandian, Lower Greensand, Headon Beds and London Clay'²; in the Lower Permian rocks at Skilaw Clough and Bentley Brook, Ormskirk³; in the Northampton Ironstone (Inferior Oolite)⁴; in the Upper Kimmeridge Clay and Portland Sand of Thame, etc., Buckinghamshire⁵; in the Spilsby Sandstone (Lower Cretaceous)⁶; in the Boulder Clay of Dimplington, Yorkshire⁷; in the dune sands of South Wales⁸; deep brown prisms in superficial deposits, Mont Pelee, Martinique⁹; in the shore sand, Kynance Cove, Cornwall¹⁰; in the sands of the Northumberland Coast¹¹; in the sands of Red Wharf Bay, Anglesey¹²; in the Clyde Alluvium, Scotland¹³.* For *Enstatite*, the less ferriiferous variety of rhombic pyroxene, see p. 101.

Possible Sources of Derivation. Intermediate, basic and ultrabasic igneous rocks, e.g. gabbro (norite), dolerite, basalt and volcanic rocks generally.

REMARKS.—If hypersthene is anticipated in a sample, avoid using strong HCl in cleaning; some varieties are readily attacked by acid, enstatite being more stable in this respect. The variety 'bronzite' is characterized by distinctive lustre and 'schiller' inclusions: see also under *enstatite*, p. 101.

References

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.
- ² P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, **18**, 1926–27, p. 140.
- ³ M. Workman, *Proc. Liverpool Geol. Soc.*, **13**, 1923, p. 308.
- ⁴ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 381.
- ⁵ E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 250.
- ⁶ F. T. Ingham, *Proc. Geol. Assoc.*, **40**, 1929, p. 1.
- ⁷ A. Raistrick, *Geol. Mag.*, **66**, 1929, p. 337.
- ⁸ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 324.
- ^{9, 10} Author's observations.
- ¹¹ L. Hawkes and J. A. Smythe, *Geol. Mag.*, **68**, 1931, p. 345.
- ¹² P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, **15**, 1928, p. 60.
- ¹³ B. H. Barrett, *Trans. Geol. Soc. Glasgow*, **17**, 1926, p. 402.

General Reference

- N. F. M. Henry, Some Data on the Iron-Rich Hypersthene, *Miner. Mag.*, **24**, 1935, p. 221.

IDDINGSITE

Chem. Comp. $\text{MgO} \cdot \text{Fe}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Pseudomorphous (usually after olivine). Lamellar.

Structure. Crystalline, aggregated.

Cleavage. Perfect \parallel (100), (001), (010); fair \parallel (101).

Fracture. Uneven.

Hardness. 3.

Spec. Grav. 2.5–2.84.

Lustre. Vitreous.

Colour. Red, reddish-brown, translucent.

Mag. Prop. Moderately magnetic.

Elect. Prop. Weak conductor.

Opt. Prop. Variable with composition. R.I. high, $\alpha = 1.674$, $\beta = 1.715$, $\gamma = 1.718$. Birefringence strong, $\gamma - \alpha = 0.044$. Optically biaxial, negative (also more rarely positive). Optic axial plane \parallel (010). $X = a$. $Y = b$. $2V = 35^\circ \pm$. $2E = 62^\circ$. Dispersion strong, $\rho > \nu$. Pleochroism: $X < Y < Z$ (in red-brown grains).

Characters in Sediments. Irregular grains of red or reddish brown colour, characterized by cleavages (as above), high relief and distinctive pleochroism.

Occurrence. In certain soils of the U.S.A.^{1,2}; in sea-beds deposit in the area between Corsica, Sardinia and Sicily³.

Possible Sources of Derivation. Olivine (in basic igneous rocks).

References

- ¹ G. N. Coffey, *U.S. Bur. Soils, Bull.* **85**, 1912.
² W. H. Fry, *Econ. Geol.*, **10**, 1915, p. 292.
³ F. Salmoiraghi, *Rend. R. Ist. lomb.*, **42**, 1909, p. 719.

ILLITE*

This is not a specific mineral, but a term originally proposed to cover the mica-like clay minerals¹. 'The name is used in two ways: for micaceous clays in general; and preferably for a mineral with the composition of Muscovite or Hydromuscovite but giving a line-poor X-ray powder pattern'². According to G. W. Brindley³ the hydrous micas include the following specific minerals:

Brammallite	Illidromica
Bravaisite	Illite
Glauconite	Illite-Chlorite (mixed layer minerals)
Hydrobiotite	Illite-Montmorillonite (mixed layer minerals)
Hydromuscovite	Sericite

The inclusion of 'illite' in this chapter is primarily to draw attention to relevant references in the study of clay minerals where the term is used, to which the reader is directed for detailed information.

References

- ¹ R. E. Grim, *Clay Minerals* (McGraw-Hill, New York), 1953, p. 35, and refs. cited.
² M. H. Hey, *Index of Mineral Species and Varieties* (Brit. Museum), 1950, p. 135, and refs. cited.
³ G. W. Brindley, *X-ray Identification and Crystal Structures of Clay Minerals* (Miner. Soc., London), 1951, pp. 326, 327.

See also:

- A. Brammall and J. G. C. Leech in *Chronic Pulmonary Disease in South Wales Coalminers; II.—Environmental Studies*, B, *Med. Res. Council, Spec. Rep.* **244** (H.M. Stationery Office), 1943, p. 127 *et. seq.*

ILMENITE

(MANACCANITE)

Chem. Comp. $\text{FeO} \cdot \text{TiO}_2$.

System. Trigonal.

Habit. Rhombohedral (10 $\bar{1}$ 1) with prominent base (0001); lamellar. Twinning on (0001) and (10 $\bar{1}$ 1).

Structure. Crystalline or in compact platy masses.

Cleavage. None. Parting sometimes developed \parallel (0001) and in twin crystals.

Fracture. Conchoidal.

Hardness. 5–6.

Spec. Grav. 4.5–5.

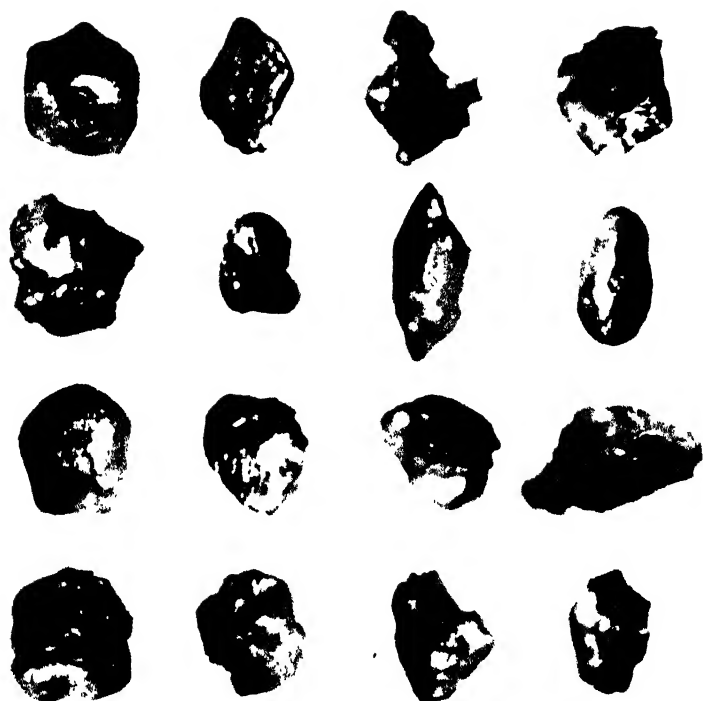
Lustre. Submetallic, steel-grey, often with crimson or purplish sheen.

* See also Ch. III, p. 316.



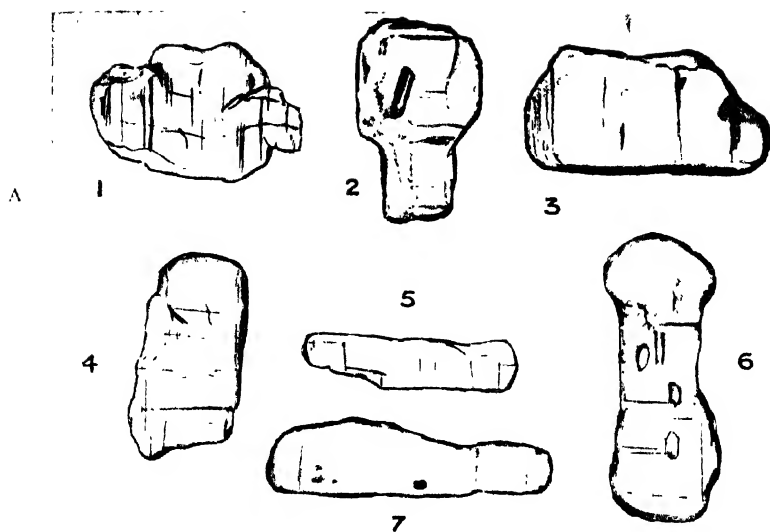
GOLD

Antioquia, Colombia, S. America [Top light, x 40]



IRIDOSMINI.

Platinum Deposits. District of Ekaterinburg, Ural Mountains, U.S.S.R.
[Top & trans. light, $\times 40$]



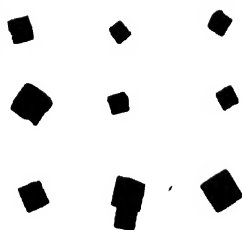
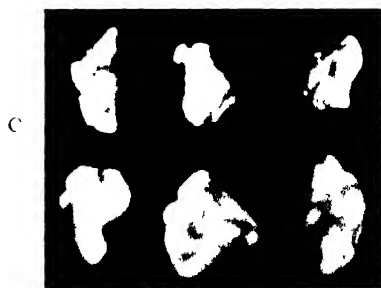
A KYANITE

- A 1, 7 Lower Greensand, N. W. Wiltshire [x 60]
 A 2, 3 Alluvials, West Africa [x 60]
 A 4, 6 Bagshot Sands, Hampstead Heath, London [x 60]
 A 5 Pliocene Sands, St. Agnes, Cornwall [x 60]



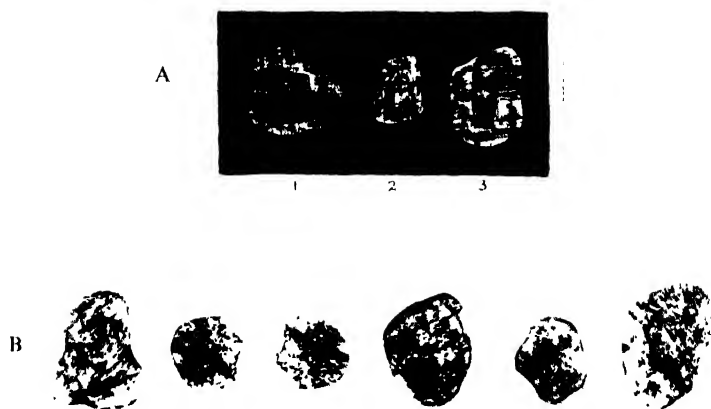
B LEUCOCINE

Upper Eocene, Auvers-sur-Oise, nr. Paris [x 40]



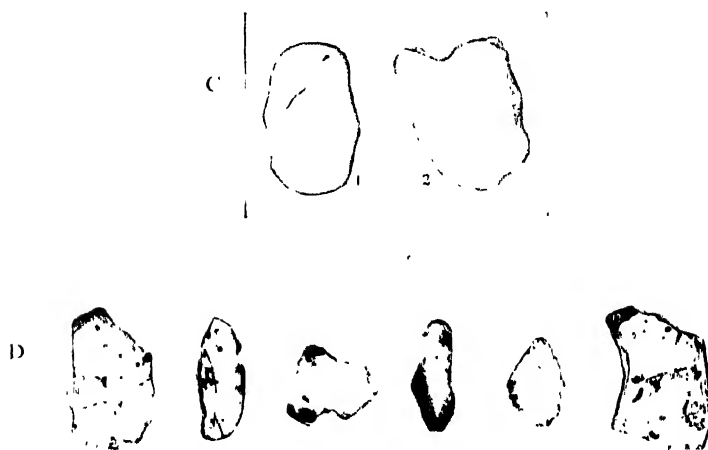
C, D. LIMONITE.

- C After Glauconite, U. Greensand, Surrey [x 59]
 D After Pyrite, Keuper, Yorkshire [x 41]



A, B MICROCTINI (x *Nicolis*)

- A 1, 2 Torridon Sandstone Skye, N.B. [x 40]
 A 3 Abbotsbury Iron Ore (Corallian), Abbotsbury, Dorset [x 40]
 B Permian, Cumberland [x 25]



C, D. MUSCOVITI.

- C 1, 2 Kelloways Rock, near Malton, Yorks. [x 65]
 D Bagshot Sands, Essex. [x 42]

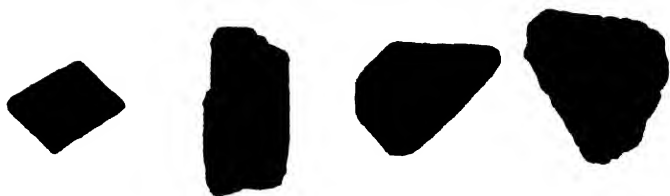


FIG. 40. Ilmenite.

1-3. Demerara, British Guiana. [$\times 60$.]4. Alluvials, Ceylon. [$\times 20$.]**Colour.** Iron-black.**Mag. Prop.** Moderately magnetic.**Elect. Prop.** Good conductor.**Opt. Prop.** Opaque, purplish-brown in very thin section, when it is translucent (edges of grain), exhibiting a high R.I. and very strong birefringence.**Characters in Sediments.** Commonly occurring in irregular, subangular grains, with characteristic purple-grey or sometimes crimson sub-metallic lustre in reflected light. Grains quite opaque in transmitted light. Partial alteration to leucoxene (p. 137) observed sometimes.**Occurrence.** An ubiquitous species in detrital sediments; far commoner than any other iron-ore, including magnetite. Recorded from deposits of every stratigraphical horizon: Pre-Cambrian to Recent. For alluvial types see C. Raeburn and H. B. Milner, *Alluvial Prospecting*, (Murby, London), 1927, p. 398.**Later Records.** In Lower Greensand, East Kent¹; in Lower Greensand, Western Weald²; in Beach Sand, Carbis Bay, Cornwall³.**Possible Sources of Derivation.** Igneous rocks, especially basic and ultrabasic types.

REMARKS.—Ilmenite frequently presents characters which render discrimination between it and associated magnetite a matter of great difficulty under the microscope. Strong dark ground illumination may aid its identification and an initial concentration can also be effected by extracting the magnetite with a powerful horseshoe or bar magnet. Where partial alteration to leucoxene occurs, there may be little fear of confusion, but it is to be noted that titaniferous magnetite may show much the same characteristics and tendencies.

References¹ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.² G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.³ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 78.**IRIDOSMINE**

[Pl. 26, between pp. 128-129]

Chem. Comp. Ir, Os (Ir > Os): see under *Remarks*.**System.** Hexagonal.**Habit.** Tabular || (0001). Occasionally prismatic.

Structure. Generally in flat polygonal grains devoid of structure.

Cleavage. Perfect \parallel (0001).

Fracture. Uneven when brittle; generally malleable.

Hardness. 6-7.

Spec. Grav. 19-21.

Lustre. Metallic.

Colour. Tin-white.

Mag. Prop. Non-magnetic.

Elect. Prop. —

Opt. Prop. Opaque.

Characters in Sediments. In cleavage flakes or flattened grains in alluvial deposits, often associated with platinum, gold, chromite, olivine (ultrabasic rock debris). Characteristic tin-white, metallic lustre.

Occurrence. In alluvial deposits of Bingera, New South Wales¹; in gold-bearing conglomerates, Witwatersrand, S. Africa²; in gold-bearing sands, N. California and S. Oregon³; in alluvial deposits, Ekaterinburg district, Urals, U.S.S.R.⁴.

Possible Sources of Derivation. Basic and ultrabasic igneous rocks.

REMARKS. Osmiridium (Siserskite) is an alloy of Os and Ir where Os > Ir. Physical characteristics similar to Iridosmine. Both varieties should be confirmed chemically† or by other (physical) tests.

References

^{1, 2, 3, 4} J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), I, 1944, p. 111 and refs. cited (p. 113).

General Reference

† C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, pp. 308, 400.

JASPER

(VARIETY OF CHALCÉDONY, *q.v.* p. 73)

KAOLINITE*

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Flattened \parallel (001); pseudo-hexagonal or rhombohedral plates often curved.

Structure. Commonly amorphous, powdery or in laminated aggregates; more rarely crystalline.

Cleavage. Perfect basal \parallel (001).

Fracture. Irregular.

Hardness. 2-2.5.

Spec. Grav. 2.6-2.63.

Lustre. Pearly on (001), otherwise dull or earthy.

Colour. White, yellow or brown. Translucent.

Mag. Prop. Non-magnetic.

* See also Ch. III, p. 308.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.561$, $\beta = 1.565$, $\gamma = 1.566$. Birefringence weak, $\gamma - \alpha = 0.005$. Optically biaxial, negative. Optic axial plane $\perp (010)$. $Bxo = Z \perp (010)$. $Bxa = X$ inclined at 4° to c. $Z \parallel b$. Y nearly $\parallel a$. $2V = 10^\circ - 57^\circ$. Dispersion weak, $\rho > \nu$. Coloured crystals pleochroic, $X =$ colourless. $Y = Z =$ cream-buff, or $X =$ cream-buff, $Y = Z =$ dark olive, buff (*A. N. Winchell*).

Characters in Sediments. Occurs commonly as irregular, colourless aggregates, wisps or as pseudo-rhombohedral scaly masses, characteristic of the light material of the sediment. Very perfect euhedra are sometimes obtainable from certain clays: see Fig. 41.

Occurrence. In clays related to 'bentonite', U.S.A.¹; in Pliocene silts of St. Agnes, Cornwall²; in the recent volcanic soil of Java³.

Later Records. In Northampton Sand Ironstones, Northamptonshire⁴; in Liassic Ironstones, Cleveland, Yorkshire⁵.

Possible Sources of Derivation. Altered acid igneous and aluminous rocks. Common alteration product of feldspar; clays.

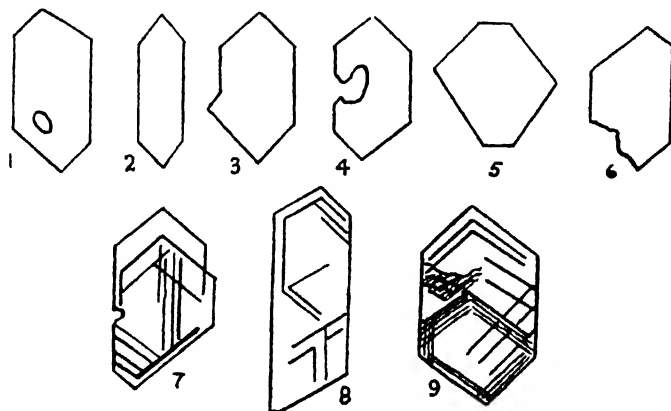


FIG. 41. Kaolinite from Clay. 1-6, Denver, Colorado, 7-9, Amlwch.

REMARKS. Kaolinite may be confused with muscovite, from which it may be distinguished by its lower R.I., birefringence and by absence of good interference figure (characteristic of mica) in (001) cleavage flakes. It is a mineral easily overlooked. *Anauxite* ($Al_2O_3 \cdot 3SiO_2 \cdot 2H_2O$) is a variety of kaolinite high in silica. Some of the Amlwch material is probably dickite (p. 94).

References

- ¹ C. S. Ross and E. V. Shannon, *Journ. Amer. Ceramic Soc.*, **9**, 1926, p. 77.
- ² H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 357.
- ³ D. A. Carroll, *Journ. Roy. Soc. West Australia*, **20**, 1933-34, p. 100.
- ⁴ J. H. Taylor, *Mem. Geol. Surv.*, 1949, p. 3.
- ⁵ T. H. Whitehead and ors., *Mem. Geol. Surv.*, 1952, p. 26.

General References

- C. S. Ross and P. F. Kerr, *The Kaolin Minerals*, *Geol. Mag.*, **69**, 1932, p. 188.
 G. W. Brindley, *X-ray Identification and Crystal Structures of Clay Minerals* (Miner. Soc., London), 1951.
 R. E. Grim, *Clay Mineralogy* (McGraw-Hill, New York), 1953.

KUNZITE

(VARIETY OF SPODUMENE, *q.v.* p. 184)

KYANITE

[Vol. I, Pl. 8, facing p. 224, and Pl. 27A, between pp. 128-129]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$.*System.* Triclinic.*Habit.* Elongated prismatic ('bladed') crystals $\parallel c$ with irregular terminations. Fibrous. Distorted crystals not uncommon. Lamellar twinning about (100).*Cleavage.* Perfect $\parallel (100)$, fair $\parallel (010)$, trace $\parallel (001)$. Parting planes $\parallel (001)$ and (308) in twin crystals.*Fracture.* Ragged.*Hardness.* Varies from 4-7 with direction: 4-5 on (100) \parallel length of crystal, 7 on (010).*Spec. Grav.* 3.6-3.68, being higher in coloured varieties.*Lustre.* Vitreous, pearly.*Colour.* Colourless, white, greyish-green, blue. Transparent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. high, $\alpha = 1.712$, $\beta = 1.720$, $\gamma = 1.728$. Birefringence moderate, $\gamma - \alpha = 0.016$. Optically biaxial, negative. Optic axial plane inclined at 30° to prism-edge (100) (010). $Bxa = X$ almost $\perp (100)$. Oblique extinction on (100), $Z \wedge c = 27^\circ - 32^\circ$; on (010) $Z \wedge c = 5^\circ - 8^\circ$; on (001) $X \wedge a = 0^\circ - 2.5^\circ$. $2V = 82^\circ - 84^\circ$. Pleochroism slight in deeply coloured varieties: $X =$ colourless, $Y =$ violet-blue, $Z =$ dark cobalt blue. Dispersion slight, $\rho > \nu$.*Characters in Sediments.* Varies greatly in physical characters, the commonest type being the subangular prismatic grain (100), elongated in the direction of the principal axis, irregularly terminated and with or without traces of the (001) cleavage (? parting) at right angles to the length of the grain and (010) cleavage parallel to the prism-margins. A more abraded form is the short 'stumpy' grain, usually well rounded and sometimes exhibiting re-entrants due to fracture of the prism face or to solution. Compound cleavage fragments, due to differential abrasion of (100) and (010) are often observed, re-entrants in such cases being very marked; these fragments are usually sharply angular. Grains flattened $\parallel (010)$ are rare: they give straight extinction and do not show the interference figure typical of the (100) grains. Markedly 'frayed' grains probably due to corrosion. Pleochroic grains are extremely rare. Inclusions of carbonaceous matter common. In some of the older sedimentary deposits 'shimmer-aggregates'

are found; these consist of colourless cores of kyanite surrounded by cryptocrystalline micaceous material containing abundant inclusions. Such aggregates are for the most part decomposition products of kyanite and allied aluminous silicates. (H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 627.)

Occurrence. Numerous records in post-Armorican deposits. In Upper Lias-Inferior Oolite, West of England^{*1}; in the Northampton Ironstone (refer specially for notes on decomposition)²; in the Portland Sand of Dorset³; in the Ashdown Sand, Hastings, Sussex⁴; in the Carstone (Lower Greensand) of Yorkshire and Lincolnshire⁵; in the Lower Greensand of Norfolk, Bedfordshire etc.⁶; in the Thanet Sands, Reading Beds and London Clay of the N.E. London Basin^{*7}; in the Bagshot Beds of Essex⁸; in the Pliocene deposits of St. Erth and St. Agnes, Cornwall^{*9}; in the later Tertiary deposits of the East of England¹⁰; in the dune sands of South Wales¹¹. (N.B.—Occurrences denoted * are figured in the appropriate references below.)

Later Records. In Lower Greensand, Western Weald¹²; in Reading Beds, Reading¹³; in mineral matter, Trinidad Lake Asphalt, B.W.I.¹⁴.
Possible Sources of Derivation. Metamorphic rocks, especially mica schist and certain gneisses.

REMARKS.—Owing to the variety of forms presented by this mineral in sediments, it is a valuable species for correlation purposes, since detailed study shows that certain types are characteristic of definite horizons. Kyanite frequently affords direct evidence of the source of origin of the material in which it occurs and by the degree of abrasion suffered it may signify the nature and potency of the transporting medium. It is found associated with garnet, staurolite, andalusite and corundum in many instances, both in metamorphic rocks and in relevant detrital sediments.

References

- ¹ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 254.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 384.
- ³ M. P. Latter, *Proc. Geol. Assoc.*, 37, 1926, p. 84.
- ⁴ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 315.
- ⁵ H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, 20, 1926, p. 349.
- ⁶ R. H. Rastall, *Geol. Mag.*, 1919, pp. 214, 271.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, pp. 577, 579 and Pl. 47.
- ⁸ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 379.
- ⁹ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 371.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 342.
- ¹¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 325.
- ¹² G. V. Wood, *Proc. Geol. Assoc.*, 67, 1956, p. 127.
- ¹³ P. S. Walder, *Proc. Geol. Assoc.*, 51, 1940, p. 215.
- ¹⁴ Author's observations.

General References

- C. H. Edelman and D. J. Doeglas, Ueber Umwandlungserscheinungen an detritischem Staurolith und anderen Mineralien, *Tschermaks Min. und Pet. Mitt.*, 45, 1934, p. 225.

F. Smithson, *Geol. Mag.*, 78, 1941, p. 97 and *Quart. Journ. Geol. Soc.*, 98, 1942, p. 27.

LABRADORITE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. Ab_2An_3 . $\text{Ab}_{50}\text{An}_{50}$ — $\text{Ab}_{30}\text{An}_{70}$ (A. N. Winchell).

System. Triclinic.

Habit. Tabular || (010). Polysynthetic twinning on (010) almost invariable. Other laws common (see albite, p. 31).

Structure. Crystalline, massive granular.

Cleavage. Perfect || (001), (010), imperfect || (110).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 2.69–2.72.

Lustre. Vitreous, pearly.

Colour. Colourless, grey, green. Iridescence on (010).

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.559$, $\beta = 1.563$, $\gamma = 1.568$. Birefringence weak, $\gamma - \alpha = 0.009$. $Bxa \rightarrow Z$ inclined at 55° – 65° to (010) and 30° – 40° to (001). $Bxo = X$ inclined at 15° – 25° to (001) and 8° – 20° to (010). $2V = 79^\circ$, $2E = 172^\circ$. Dispersion weak, $\rho > \nu$.

Characters in Sediments. Labradorite when found in sediments as individual grains is diagnosed by extinction angle measured from twin lamellae (30° – 40°), by the 'broadness' of these lamellae and by the R.I. being greater than that of Canada balsam. Grains which do not exhibit such features are almost certain to be overlooked. Most detrital plagioclase feldspar is determined by cleavages, but labradorite does not seem to survive commonly in sediments. Inclusions of hematite and ilmenite are usual, other possibilities being pyroxenes and amphiboles. Prone to rapid alteration to sericitic mica, kaolinite or 'sausserite', which may account for the comparatively scanty records of this species.

Occurrence. In the recent volcanic soil of Java¹; in sands at Foily Beach, near Charleston, S. Carolina, U.S.A.².

Possible Sources of Derivation. Basic igneous rocks.

References

¹ D. A. Carroll, *Journ. Roy. Soc. West Australia*, 20, 1933–34, p. 100.

² J. H. C. Martens, *Amer. Min.*, 16, 1931, p. 526.

LAWSONITE

Chem. Comp. $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Prismatic, tabular. Twinned on (110).

Structure. Crystalline.

Cleavage. Perfect || (010) and (001); less perfect || (110).

Fracture. Uneven.

Hardness. 8.

Spec. Grav. 3.1.

Lustre. Vitreous, dull.

Colour. Colourless, blue.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.665$, $\beta = 1.674$, $\gamma = 1.699$. Birefringence strong, $\gamma - \alpha = 0.034$. Optically biaxial, positive. Optic axial plane \parallel (010). $Z = c$, $X = a$. Straight extinction \parallel prism edge and (010) cleavage trace. $2V = 84^\circ$. Dispersion strong, $\rho > v$. Pleochroic in thick sections; $X = \text{blue}$, $Y = \text{yellow}$, $Z = \text{colourless}$.

Characters in Sediments. Usually a secondary mineral, often after lime-soda feldspar in basic rocks. Occurs as colourless or slightly blue prismatic or irregular grains characterized by high relief and cleavage. Liable to confusion with zoisite, but has stronger birefringence than that species; also with cordierite; the latter has more pronounced pleochroism, lower R.I. and is negative.

Occurrence. In the Miocene rocks of Central Italy¹; at the base of the San Onofre Breccia, California (Lower Miocene)²; in the Tiburn Peninsula, Marin Co., California and in the Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California³.

Possible Sources of Derivation. Metamorphic rocks, schists; saussuritized gabbro.

References

¹ I. Chelussi, *Atti Soc. Lig. Sci. nat.*, **21**, 1910, p. 105.

² A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, **21**, 1925, p. 159.

³ R. D. Reed and J. B. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, **11**, 1927, p. 363.

LEPIDOLITE

(MICA GROUP)

Chem. Comp. $2H_2O \cdot K_2O \cdot Li_2O \cdot 2Al_2O_3 \cdot 6SiO_2$ (A. F. Hallimond).

System. Monoclinic. ? Triclinic.

Habit. Tabular \parallel (001) with pseudo-hexagonal or irregular outline; sometimes elongated. Twinning about plane \perp (001) common; contact plane (001).

Structure. Crystalline, laminated.

Cleavage. Perfect \parallel (001). Parting \parallel (010) and \parallel (111). Parting and gliding planes \parallel various crystal faces produced by percussion.

Fracture. Irregular, but rarely seen.

Hardness. 2.5-4.

Spec. Grav. 2.8-2.9.

Lustre. Vitreous to pearly.

Colour. Lilac to mauve, white, yellow, grey, pink. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.532$, $\beta = 1.555$, $\gamma = 1.555$. Birefringence moderate, $\gamma - \alpha = 0.023$. Optically biaxial, negative. Optic axial plane \perp (010). Bxa nearly \perp cleavage plane (001), hence most flakes yield

good interference figure. $2E$ varies from 57° – 84° ; $2V = 0^{\circ}$ – 50° . Pseudo-uniaxial varieties also noted. Sometimes distinctly pleochroic: Y and Z = lilac or pink, X = colourless. Dispersion, $\rho > \nu$.

Characters in Sediments. Occurs much as muscovite does, in irregular cleavage flakes, but of characteristic lilac to mauve colour. The refractive index is higher than that of muscovite and the birefringence is also higher. Intimate association with muscovite (zonal structure) in the same flake may sometimes be noted. Inclusions are usually absent, a further point of distinction from white mica; where recorded they have been identified as rutile, zircon, cassiterite or topaz, usually with pleochroic haloes.

Occurrence. Hitherto unrecorded from British sediments. Mauve-coloured mica flakes are noted from time to time in sands, e.g. shore sands of East Anglia, which may be referable to this species. Not uncommon in some of the late Tertiary sands of the Los Angeles basin, S. California, U.S.A.¹.

Possible Sources of Derivation. Granite, pegmatite. Pneumatolytic ore-bodies, e.g. topaz, cassiterite etc.

REMARKS.—Lepidolite is to some extent attacked by hydrochloric acid, so that flakes may show etching or apparent alteration due to the initial cleaning of the sediment. Muscovite is not thus affected.

Reference

¹ Author's observations.

LEPIDOMELANE

(MICA GROUP)

Chem. Comp. Biotite rich in ferric iron; also containing TiO_2 .

System. Monoclinic.

Habit. Tabular, scaly. Pseudo-hexagonal six-sided prisms. Twinned on (110) in thin (001) laminae.

Structure. Crystalline, massive, lamellar.

Cleavage. Perfect \parallel (001). Parting \parallel (010) and (111).

Fracture. Uneven.

Hardness. 3.

Spec. Grav. $3.1 \pm$.

Lustre. Vitreous, resinous, pearly.

Colour. Black, dark brown. Translucent to opaque.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.615$, $\beta = 1.726$, $\gamma = 1.733$. Birefringence very strong, $\gamma - \alpha = 0.118$. Optically biaxial, negative (sometimes uniaxial, negative with $\omega = 1.64$, birefringence 0.05). Optic axial plane \parallel (010). $2V = 31^{\circ}$. $X \wedge c = \text{small}$. $Y = b$. $2E = 52^{\circ}$. Dispersion strong, $\rho < \nu$. Pleochroism weak: Z = dark brown to opaque, Y = dark brown to opaque, X = light brownish-yellow.

Characters in Sediments. As biotite, but distinguished by its dark colour, rich blackish-brown pearly lustre by reflected light, high R.I.

and strong birefringence. Most flakes are basal and when thin enough yield discernible negative interference figures. Optical properties of lepidomelane vary with iron content.

Occurrence. Listed by P. G. H. Boswell¹.

Possible Sources of Derivation. Intermediate plutonic rocks, *e.g.* syenite, metamorphic rocks.

Reference

¹ *On the Mineralogy of Sedimentary Rocks* (Murby, London), 1933, p.6.

LEUCOXENE

[Pl. 27B, between pp. 128-129]

Chem. Comp. A decomposition product of ilmenite, as yet ill-defined.

It is probably for the most part a form of titanium dioxide (rutile or anatase); titanite has also been suspected, with possibly some carbonate. It has been described by J. P. Iddings as a form of anatase or perovskite and by S. A. Tyler and R. W. Marsden as rutile (see ref. below).

System. Non-crystalline.

Habit. Irregular aggregates or as pseudomorphs after ilmenite.

Structure. Amorphous.

Spec. Grav. Varies from 3.5-4.5.

Lustre. Dull.

Colour. White, yellow or brown. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. High R.I. and birefringence, seen in translucent flakes.

Characters in Sediments. Commonly occurs as rounded grains, opaque in transmitted light, white or yellowish-white in reflected light, having an 'unglazed porcelain' appearance. Sometimes a core of unaltered ilmenite may be observed, in which case the grain will appear weakly magnetic. A rough 'pitted' surface is characteristic of most grains, best seen by reflected light. Where the mineral is reasonably translucent, aggregate polarization may be observed with crossed nicols.

Occurrence. Ubiquitous in detrital sediments as with ilmenite (p. 128).

Later Records. In Lower Greensand, East Kent¹; in Lower Greensand, Western Weald².

Possible Sources of Derivation. Essentially from ilmenite and largely *in situ*.

References

¹ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.

² G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

General References

L. S. Brown, The Occurrence of Leucoxene in some of the Permian Mid-Continent Sediments, *Amer. Min.*, **13**, 1928, p. 233.

F. Coil, Chemical Composition of Leucoxene in the Permian of Oklahoma, *Amer. Min.*, **18**, 1933, p. 62.

S. A. Tyler and R. W. Marsden, *The Nature of Leucoxene*, *Journ. Sed. Pet.*, 8, 1938, p. 55.

LIMONITE

[Pl. 27C, D, *between pp.* 128-129]

Chem. Comp. $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}?$

System. Non-crystalline.

Habit. Varied; pseudomorphous after iron-ores.

Structure. Amorphous, earthy.

Fracture. Uneven.

Hardness. $4 \pm$.

Spec. Grav. $3.8 \pm$.

Lustre. Submetallic, dull.

Colour. Dark brown, yellowish-brown.

Mag. Prop. Varies according to degree of alteration of the original mineral from which it was derived; essentially non-magnetic *per se*.

Elect. Prop. Moderate conductor.

Opt. Prop. Opaque. R.I. very high, $n = 2.05 \pm$. Seen occasionally on thin edges of grains.

Characters in Sediments. Of frequent occurrence as irregular grains and as powdery aggregates. It has a brown, ochreous colour by reflected light, being opaque in transmitted light except in very thin sections, when a brownish-yellow colour prevails. The translucent particles are isotropic. Limonitic pseudomorphs after marcasite, pyrite, magnetite and hematite are not uncommon, while its occurrence as a decomposition product of glauconite is often observed. It represents one of the most prevalent forms of authigenous material found in sediments.

Occurrence. Ubiquitous in detrital sediments as a cementing medium.

Possible Sources of Derivation. Iron-ores of varying composition. Iron-bearing minerals.

REMARKS.—Limonite is the commonest coating of detrital particles and its removal, prior to their microscopical analysis, necessitates the usual preliminary treatment of a sample with dilute HCl or alkali. See also goethite, p. 114. X-ray investigations have shown that most of the substance commonly named limonite is actually cryptocrystalline goethite with adsorbed or capillary water (J. D. & E. S. Dana, *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, p. 685).

MAGHEMITE

(FERROMAGNETIC FERRIC OXIDE)

Chem. Comp. $\gamma \text{Fe}_2\text{O}_3$ (magnetic hematite).

System. Isometric.

Habit. Massive.

Structure. ---

Cleavage. -

Fracture. --

Hardness. 5.

Spec. Grav. —

Lustre. Earthy.

Colour. Brown.

Mag. Prop. Strongly magnetic.

Elect. Prop. Good conductor.

Opt. Prop. When translucent, isotropic.

Characters in Sediments. The brown alteration product seen occasionally on magnetite grains is probably maghemite.

Occurrence. In Laterite deposits, Co. Antrim¹.

Possible Sources of Derivation. Magnetite; lepidocrocite. From magnetite associated with weathered basalt.

REMARKS. Related to magnetite and the spinel group.

Reference

¹ V. S. Eyles, F. A. Bannister, G. W. Brindley and J. Goodyear, *Mem. Geol. Surv., N. Ireland*, 1952, p. 42.

General Reference

J. D. and E. S. Dana, *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, p. 708.

MAGNESITE

Chem. Comp. MgO . CO₂.

System. Trigonal.

Habit. Prismatic, rhombohedral. Perfect crystals rare.

Structure. Crystalline, massive.

Cleavage. Perfect \parallel (10 $\bar{1}$ 1).

Fracture. Irregular.

Hardness. 3.5-4.

Spec. Grav. 2.96.

Lustre. Pearly, resinous.

Colour. Colourless, white, yellow, brown. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low for ϵ , high for ω ; $\epsilon = 1.509$, $\omega = 1.700$. Birefringence very strong, $\omega - \epsilon = 0.191$. Optically uniaxial, negative.

Characters in Sediments. Occurs as quite irregular grains, crystals being rare. Cleavage and 'twinkling' on rotation of polarizer are characteristic, but the mineral is difficult to distinguish microscopically unless anticipated from other evidence. Distinguished from calcite by absence of lamellar twinning, higher R.I. (for ω), higher birefringence. The S.G. of magnesite is higher than that of calcite; the latter floats, the former sinks in bromoform (2.9). Physical tests often necessary in confirmation.

Occurrence. Recorded by P. G. H. Boswell¹.

Possible Sources of Derivation. Schists, ultrabasic igneous rocks; magnesite deposits.

REMARKS.—Unlike calcite and dolomite, magnesite is insoluble in cold dilute HCl. Soluble in hot acid.

Reference

¹ *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 268.

MAGNETITE

(SPINEL GROUP)

Chem. Comp. Fe_3O_4 .

System. Isometric.

Habit. Octahedral, dodecahedral (sometimes with striations || major diagonal of crystal face) or twinned on (111).

Structure. Crystalline, granular, massive.

Cleavage. None. Parting || (111).

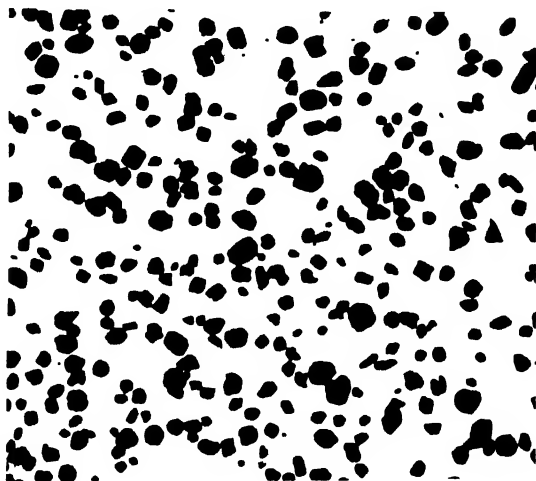


FIG. 42. Magnetite, Alluvial Sand, Colombia, S America. [$\times 20$.]

Fracture. Subconchoidal, uneven, hackly.

Hardness. 5.5–6.5.

Spec. Grav. 5.1–5.18.

Lustre. Metallic, submetallic, dull. Grey in vertical reflected light.

Colour. Silver-grey.

Mag. Prop. Strongly magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque. R.I. very high, $n = 2.42$.

Characters in Sediments. The octahedral, silver-grey or black crystals of this species are very characteristic, as also are the irregularly shaped, shiny black grains. Careful examination of some grains with powerful incident light and high power objective frequently reveals the presence of minute facets. In the absence of such faceting, the grains may have only a dull grey lustre and be difficult to distinguish from ilmenite (p. 129). Both angular and well rounded irregular grains are also common, the former often showing a marked

hackly fracture. Partial alteration to limonite is frequently observed, also to hematite or siderite.

Occurrence. Numerous records extant. The following examples have been confirmed with the bar- or electro-magnet and are so recorded by the authors concerned:—in the Upper Lias—Inferior Oolite, West of England¹; in the Pliocene deposits of Cornwall²; in the later Tertiary deposits of East of England³. Other occurrences are:—in the Old Red Sandstone of the West Midlands⁴; in the Bunter Sands of the Midlands⁵; in the Northampton Ironstone⁶; in the dune sands of South Wales⁷; in the Dartmoor detritals⁸; in the sands of the foreshore of the Carnarvon coast⁹; in certain surface deposits of Cambridgeshire¹⁰.

Later Records. In Lower Greensand, Western Weald¹¹; in Beach Sand, Carbis Bay, Cornwall¹².

Possible Sources of Derivation. Basic and ultrabasic igneous rocks.

REMARKS.—Less common in sediments than ilmenite. Distinguished from ilmenite by its lustre and crystalline form if developed and may be separated from that mineral by using a horseshoe or bar magnet, which is always the safest preliminary test in diagnosis. (See also *Maghemite*, p. 138.)

References

- ¹ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 253.
- ² H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, pp. 354, 358.
- ³ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 338.
- ⁴ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 513.
- ⁵ J. B. Scrivenor, *Mineral. Mag.*, **13**, 1903, p. 348.
- ⁶ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 379.
- ⁷ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 321.
- ⁸ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 35.
- ⁹ T. H. Cope, *Proc. Liverpool Geol. Soc.*, **9**, 1902, p. 208.
- ¹⁰ R. H. Rastall, *Proc. Cambridge Phil. Soc.*, **17**, 1913, p. 132.
- ¹¹ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
- ¹² C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 78.

MARCASITE

Chem. Comp. FeS₂.

System. Orthorhombic.

Habit. Tabular || (001); pyramidal. Commonly twinned on (110), often repeated; less common on (101); simple crystals rare.

Structure. Crystalline, fibrous, concretionary and radiating.

Cleavage. Poor || (110), imperfect || (011).

Fracture. Uneven, ragged. (Very brittle.)

Hardness. 6–6.5.

Spec. Grav. 4.8.

Lustre. Metallic, splendid. With dark ground illumination; creamy-white.

Colour. Brass-yellow to greyish-yellow.

Mag. Prop. Weakly magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque. 'Produces marked rotation of the plane of polarization of reflected light, in which it has a peculiar and characteristic pleochroism' (A. N. Winchell).

Characters in Sediments. Grains usually small, very ragged and possessing a typical greyish-yellow metallic lustre in reflected light; superficial alteration to limonite is commonly shown. Traces of radial structure noted in some examples.

Occurrence. In the Sandgate Beds (Lower Greensand), Gault, Chalk, Woolwich and Reading Beds and London Clay of the Croydon Regional Survey area (Surrey etc.)¹; in the Thanet Beds, Reading Beds and London Clay, N.E. London Basin².

Possible Sources of Derivation. Metalliferous veins; sedimentary rocks, especially chalk.

REMARKS.—Much less common than its isomer pyrite, being easily decomposed. Molluscan fragments preserved in marcasite sometimes found².

References

¹ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915–16, p. 86.

² P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, pp. 577, 581 and table iv.

General Reference

F. A. Bannister, The Distinction of Pyrite from Marcasite, etc., *Miner. Mag.*, 23, 1932, p. 179.

MELANITE

(GARNET GROUP)

Chem. Comp. $3\text{CaO} \cdot (\text{Fe}, \text{Ti})_2\text{O}_3 \cdot 3(\text{Si}, \text{Ti})\text{O}_2$.

System. Isometric.

Habit. Dodecahedral, trapezohedral with hexoctahedral modifications.

Structure. Crystalline.

Cleavage. None.

Fracture. Conchoidal.

Hardness. 7.

Spec. Grav. 3.7.

Lustre. Vitreous, resinous. Translucent to opaque.

Colour. Black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. very high, $n = 1.94$. Optically isotropic.

Characters in Sediments. Occurs as black, usually subangular dodecahedral grains, often with characteristic striations ‡ (110).

Occurrence. In the Silurian Rocks of Southern Scotland¹; in surface deposits derived from disintegration of melanite-syenites of the Assynt district, Scotland².

Possible Sources of Derivation. Metamorphic rocks (contact-altered limestones). Syenite. Acid igneous rocks.

REMARKS.—Melanite is really the black variety of *andradite* (*q.v.* p. 41) in which titanium replaces in part iron and also silica. The grey-black variety is sometimes known as '*schorlomite*', which may also be considered a variety of andradite.

References

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.
- ² J. J. H. Teall, *Geology of the N.W. Highlands*, *Mem. Geol. Surv. Scotland*, 1907, p. 442.

MICROCLINE

(FELSPAR GROUP)

[Pl. 28A, B, between pp. 128–129]

Chem. Comp. $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$.

System. Triclinic.

Habit. Prismatic, frequently twinned according to Carlsbad, Baveno and Manebach laws; also shows fine microscopic lamellar twinning (albite and pericline laws), giving rise to characteristic 'cross-hatching'. Crystals similar to orthoclase (*q.v.* p. 155).

Structure. Crystalline, massive.

Cleavage. Distinct \parallel (001), imperfect \parallel (010), more rarely \parallel (110) and $\{201\}$. Parting \parallel (100) occasionally seen.

Fracture. Conchoidal, uneven.

Hardness. 6.

Spec. Grav. 2.55.

Lustre. Vitreous.

Colour. White, yellow, green or red. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. low, $\alpha = 1.522$, $\beta = 1.526$, $\gamma = 1.530$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial, negative. Optic axial plane nearly (010). $Bxa = X$ inclined at small angle ($< 5^\circ$) to axis a. $Bxo = Z$ nearly \perp (010). $2V = 83^\circ$. (001) flakes give oblique extinction, 16° and (010) flakes give 5° , measured from the trace of (010) and (001) cleavages respectively. (001) plates invariably show characteristic 'cross-hatched' structure. Dispersion weak, $p > v$.

Characters in Sediments. Platy basal grains (001) are the most common, easily recognized by the characteristic 'cross-hatching' in polarized light. Other forms, such as (010) cleavage fragments, are rarer. In most examples the grains present irregular outlines, sometimes due to corrosion (see ref. ¹³ below). Inclusions are sometimes seen; these may be primary muscovite (distinct from that occurring as a decomposition product), zircon, iron-ores or quartz. Decomposition to muscovite or kaolinite renders grains greyish-white by reflected light and causes the appearance of highly polarizing aggregates between crossed nicols.

Occurrence. In the Torridon Sandstone of N.W. Highlands and of S.E. Skye, N.B.¹; in the Malvern quartzite²; in the Old Red Sandstone, Cardiff district³; in the Old Red Sandstone, West Midlands⁴; in the

Millstone Grit, Yorkshire⁵; in the Middle Permian sands of Yorkshire⁶; in the New Red Sandstone, West of England⁷; in the Northampton Ironstone⁸; in the Abbotsbury Iron-Ore (Corallian), Dorset⁹; in the later Tertiary deposits, East of England¹⁰; in surface deposits of S.E. Devonshire¹¹; in sands of the Northumberland Coast¹².

Later Records. In Millstone Grit, Anglesey¹³.

Possible Sources of Derivation. Acid igneous rocks. Metamorphic rocks.

REMARKS.—See also *anorthoclase*, the soda-microcline (p. 45). *Perthite* and *micropertthite* are names given to regular intergrowths of microcline (or orthoclase, p. 155) with albite (p. 31). Recorded from the New Red Sandstone of the West of England¹⁴; from the Mallee Soil of W. Australia¹⁵.

References

¹ Author's observations; see also *Mem. Geol. Surv. Scotland*, N.W. Highlands, 1907, ch. xvi.

² G. S. Sweeting, *Proc. Geol. Assoc.*, **38**, 1927, p. 551.

³ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 508.

⁴ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 512.

⁵ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 262.

⁶ H. C. Versey, *Proc. Yorks. Geol. Soc.*, **20**, 1925, p. 205.

⁷ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 239.

⁸ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 385.

⁹ Author's observations.

¹⁰ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 336.

¹¹ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 148.

¹² L. Hawkes and J. A. Smythe, *Geol. Mag.*, **68**, 1931, p. 345.

¹³ F. Smithson, *Geol. Mag.*, **91**, 1954, p. 177.

¹⁴ H. H. Thomas, *loc. cit.*, p. 291.

¹⁵ D. A. Carroll, *Journ. Roy. Soc. W. Australia*, **20**, 1933–34, p. 100.

General Reference

H. L. Alling, The Mineralography of the Feldspars, *Journ. Geol.*, **31**, 1923, pp. 282, 353.

MOLYBDENITE

Chem. Comp. MoS₂.

System. Hexagonal; dihexagonal dipyramidal.

Habit. Tabular, more rarely prismatic, often twinned about (0001).

Structure. Crystalline, scaley, foliated, laminated.

Cleavage. Perfect || (0001).

Fracture. Seldom developed, sectile.

Hardness. 1–1.5.

Spec. Grav. 4.62–4.73.

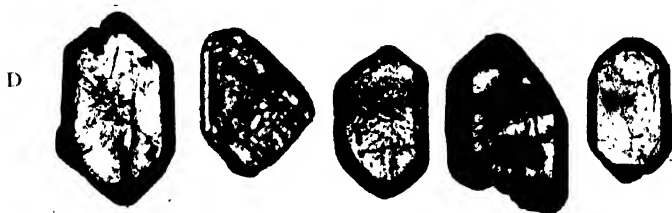
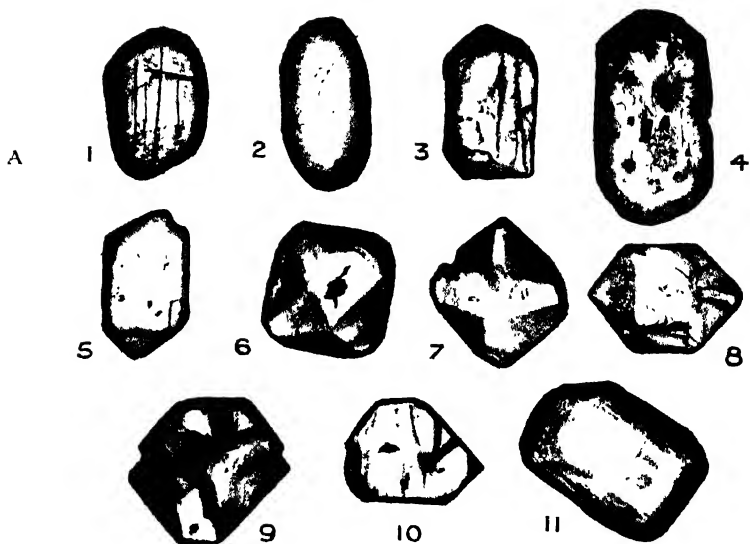
Lustre. Metallic

Colour. Lead-grey.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

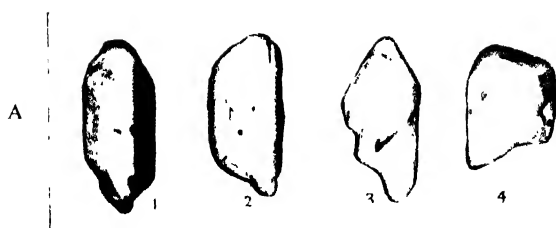
Opt. Prop. Opaque. Translucent in thin flakes with reddish-brown colour.



A D. MONAZITE.

1, 2. Recent Sands, Cape Comorin, Travancore, India [x 70]
 3-5. Recent Sands, Ceylon [x 40]
 6-11. Alluvials, Brazil. [x 70]

B Recent Sand, Travancore, India [x 43]
 C Shore Sand, Ceylon. [x 45]
 D Alluvials, Ceylon [x 12]

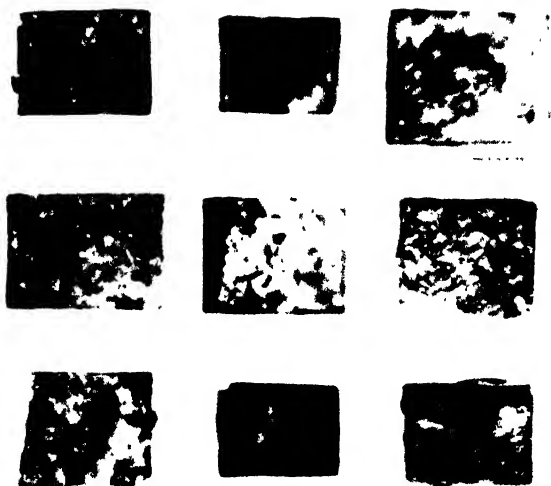


A, B OLIVINE.

A 1-4 Shore Sand, Cape Verde Is. [X 35]

B Tule Lake, Oregon U.S.A. [X 22]

A



A. PEROVSKITE, VAR. DYSANALYTE.
Kaiserstuhl, Baden, Germany [Top & trans light, $\times 40$]

B



B. PUMILLYITE.
Quaternary Deposits, Beach N. of Noordwyk aan Zee, Netherlands [$\times 50$]
(After J. H. Langenberg & W. P. De Roever *Geol. Min. (N.W. Ser.)*, 17e Jaar, 1955, p. 163)



PLATINUM.

River Deposit: R Pinto, Papayan, Dept. of Cauca, Colombia, S. America.
 [Top & trans light, x 25]

Characters in Sediments. As flattened, platy or scaly grains, of characteristic lead-grey colour and softness.

Occurrence. In Dartmoor detritals¹; in stream deposits, Brandy Gill, near source of R. Caldew, Heskett Newmarket, Cumberland²; in Shap Granite detritals, Westmorland³.

Possible Sources of Derivation. Granite, pegmatite, crystalline limestone.

REMARKS.—Detrital molybdenite is a rare mineral except in certain localized environments where appropriate parent-rocks are laid under direct contribution to stream deposits, alluvials, etc. Seldom far travelled from source of origin.

References

- ¹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 46.
- ² A. Strahan and ors., *Mem. Geol. Surv., Spec. Rep. Min. Res. Gt. Brit.*, **5**, 1916, p. 29.
- ³ Author's observations.

MONAZITE

[Pl. 29A -D, between pp. 144 145]

Chem. Comp. (Ce, La, Di)₂O₈ . P₂O₅. Some ThO₂ . SiO₂.

System. Monoclinic.

Habit. Small crystals flattened \parallel (100) with varying terminations; also elongated \parallel b or (111).

Structure. Crystalline, granular.

Cleavage. Perfect \parallel (001), good \parallel (100), less common \parallel (010), rarely \parallel (111).

Fracture. Uneven, conchoidal.

Hardness. 5.

Spec. Grav. 4.9–5.3.

Lustre. Vitreous, resinous.

Colour. Yellow, yellowish-brown, brown, red. Translucent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. very high, $\alpha = 1.800$, $\beta = 1.801$, $\gamma = 1.849$. Birefringence strong, $\gamma - \alpha = 0.049$. Optically biaxial, positive. Optic axial plane \perp (010), almost \parallel (100). $Bxa \perp Z$ inclined to principal axis c at angle of 10° . $Y \perp b$. $2E = 19^\circ$, $2V = 11^\circ$. Varieties without ThO₂, SiO₂ have lower R.I. ($\beta = 1.788$), $X \perp b$, $Z \wedge c = 2^\circ \pm$. $2V = 14^\circ$, $2E = 25^\circ$. Pleochroism seen in thick grains: $Y =$ dark yellow $\therefore X =$ light yellow $\therefore Z =$ greenish yellow. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Usually occurring as well rounded, pale yellow grains with dark border, due to R.I. effect. Colourless, or by contrast, deep brown, almost opaque grains occur. A common detrital form is the rounded, egg-shaped crystal derived from faceted tablets \parallel (100); perfect euhedra, sometimes strongly faceted, are found; (001) cleavage fragments are also frequent; these yield a good positive interference figure. A. Brammall has described and figured octagonal, hexagonal, quadrilateral and heptagonal crystal habits from the

Dartmoor detritals. Decomposition often noted superficially in the form of brown coloured patches or stains which are probably complex alteration products of cerium, etc. Inclusions often noted, chiefly gas-filled cavities. A. Brammall states that 'Suspensions of opaque dust or brown-red stains are of occasional occurrence; crystalline inclusions are rare'⁹.

Occurrence. In the Millstone Grit of Yorkshire¹; in the Northampton Ironstone²; in the Ashdown Sands and Fairlight Clays (Wealden) of the Hastings district, Sussex³; in the Lower Greensand of Surrey⁴; in the Eocene (?) of Buckland Brewer and the Oligocene of the Bovey Basin, Devonshire⁵; in the Lenham Beds of Kent etc.⁶; in the valley deposits derived from the Chipstead and Headley Sands, Surrey⁷; in Glacial deposits of the Dublin district⁸; in the Dartmoor detritals⁹.

Later Records. In Lower Greensand, East Kent¹⁰; in Lower Greensand, Western Weald¹¹; in Beach Sand, Carbis Bay, Cornwall¹²; in Residual Deposits, Muntok district, N.W. Banka, Indonesia¹³.

Possible Sources of Derivation. Acid igneous rocks, especially granites.

REMARKS.—There may be a little difficulty in diagnosing monazite under the microscope and if necessary confirmation may be obtained both chemically and spectroscopically. In the former case the phosphomolybdate reaction is sought and in the latter case the absorption spectrum with the characteristic neodymium-praseodymium bands is easily identified. The use of a spectroscopic eyepiece attachment to the petrological microscope (Vol. I, Fig. 24, p. 224) facilitates this observation.

References

- ¹ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 267.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 383.
- ³ H. B. Milner, *Proc. Geol. Assoc.*, **36**, 1925, p. 315.
- ⁴ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, p. 93.
- ⁵ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ⁶ G. M. Davies, quoted by P. G. H. Boswell: see *gen. ref.* below.
- ⁷ G. M. Davies, *loc. cit.*
- ⁸ F. Smithson, *Geol. Mag.*, **65**, 1928, p. 24.
- ⁹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 29.
- ¹⁰ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- ¹¹ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
- ¹² C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.
- ¹³ J. W. A. Bodenhausen, *Proc. Konink. Nederl. Akademie van Wetenschappen—Amsterdam*, Series B, **57**, 1954, p. 322.

General References

- F. W. Clarke, *Data of Geochemistry*, U.S. Geol. Surv., *Bull.* **770**, 5th ed., 1924, p. 359.
- P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, **18**, 1926–27, p. 137.
- C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 405 (for alluvial occurrences, monazite sands, etc.).

MONTMORILLONITE*

(MONTMORILLONITE—BEIDELLITE SERIES)

Chem. Comp. (Mg, Ca)O . Al₂O₃ . 5SiO₂ . (5-8)H₂O (C. S. Ross and E. V. Shannon).

System. ? Orthorhombic. Pseudohexagonal.

Habit. Lamellar aggregates.

Structure. Crystalline.

Cleavage. Perfect || (001).

Fracture. Irregular. Soft.

Hardness. 1.

Spec. Grav. 2.5 ±.

Lustre. Pearly.

Colour. White, pink, pale blue, green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.503$, $\beta = 1.526$, $\gamma = 1.527$. Birefringence moderate, $\gamma - \alpha = 0.024$. Optically biaxial, negative. $Bxa = X$ practically \perp (001). $2V =$ small (up to 24°).

Characters in Sediments. The essential constituent of many clays, e.g. bentonite (p. 236), Fuller's earth (p. 232), montmorillonite occurs in all stages from incipient alteration of muscovite, glauconite, spodumene, etc., to masses of minutely crystalline particles of too small a size to be determined by microscopical means alone. Particles large enough (5-10 μ) to be studied optically nearly always show emergence of $bxa \perp$ to flat surface and related properties as above.

Occurrence. In Ordovician altered volcanic material in Iowa, Wisconsin and Missouri, U.S.A.¹; in Ordovician bentonites of the Eastern United States²; in water-laid volcanic rocks of early Upper Cretaceous age in Arkansas, Oklahoma and Texas³.

Possible Sources of Derivation. Alteration product of feldspar, mica, spodumene, glauconite, etc.

REMARKS.—Montmorillonite is a member of a series of hydrated silicates characteristic of certain finely divided sediments such as clays. The series includes *beidellite* (p. 59), *nontronite* (p. 151), etc.

References

¹ V. T. Allen, *Journ. Geol.*, **40**, 1932, p. 257.

² C. A. Bonine and A. P. Honess, *Proc. Pennsylvanian Acad. Sci.*, **3**, 1929, p. 1.

³ C. S. Ross, H. D. Miser and L. W. Stephenson, *U.S. Geol. Surv., Prof. Paper 154—F.*, 1929, p. 175.

General References

C. S. Ross and E. V. Shannon, The Minerals of Bentonite and Related Clays and their Physical Properties, *Journ. Amer. Ceram. Soc.*, **9**, 1926, p. 77.

C. S. Ross and P. F. Kerr, The Clay Minerals and their Identity, *Journ. Sed. Pet.*, **1**, 1931, p. 55.

* See also Ch. III, p. 320.

- P. F. Kerr, Montmorillonite or Smectite as Constituents of Fuller's Earth and Bentonite, *Amer. Min.*, 17, 1932, p. 192.
 R. E. Grim, Petrology of Fuller's Earth Deposits, Olmstead, Illinois, *Econ. Geol.*, 28, 1933, p. 344.
 G. W. Brindley, *X-ray Identification and Crystal Structures of Clay Minerals* (Miner. Soc., London), 1951.
 R. E. Grim, *Clay Mineralogy* (McGraw-Hill, New York), 1953.

MUSCOVITE

(MICA GROUP)

[Pl. 28C, D, between pp. 128-129]

Chem. Comp. $(K, Na)_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O$.*System.* Monoclinic, pseudohexagonal.*Habit.* Tabular crystals \parallel (001). Pseudo-orthorhombic or pseudo-rhombohedral forms found.*Structure.* Well laminated, massive; individual crystals rare.*Cleavage.* Perfect \parallel (001). Parting \parallel (010) and $(\bar{1}11)$.*Fracture.* Ragged (rare).*Hardness.* 2.5-3.*Spec. Grav.* 2.76-3.*Lustre.* Vitreous, pearly.*Colour.* Colourless to yellow, deepening with thickness; grey.*Mag. Prop.* Normally non-magnetic, occasionally magnetic.*Elect. Prop.* Non-conductor.

Opt. Prop. R.I. low, $\alpha \approx 1.558$, $\beta \approx 1.595$, $\gamma \approx 1.601$. Birefringence strong, $\gamma - \alpha \approx 0.043$, but that usually seen in cleavage (001) flakes is due to $\gamma - \beta \approx 0.006$ and hence is very weak. Optically biaxial, negative. Optic axial plane \perp (010). $Z \approx b$. $Bxa = X$ practically \perp (001), hence cleavage plates always yield good interference figure. $2V \approx 40^\circ \pm$, $2E \approx 68^\circ$. Dispersion distinct, $\rho < \nu$.

Characters in Sediments. Commonly in thin, colourless platy grains (001), with characteristic low R.I., bluish-grey interference tint and good figure. Other forms extremely rare. Grains usually rounded and often from three to four times larger than the average grade-size of associated minerals. Inclusions are common, such as zircon, rutile, tourmaline, apatite, spinel, quartz, iron ores and garnet. Undulose extinction is a feature of some varieties, implying derivation from metamorphic rocks.

Occurrence. In the Torridonian Sandstone, S.E. Skye, N.B.¹; in the Hollybush Sandstone (Cambrian) of the Malvern district²; in Cambrian shales, Ordovician and Silurian sands, Lower Devonian sandstone of the English Midlands³; in the May Hill Sandstone (Silurian) of the Malvern district⁴; in the Downtonian of the West Midlands⁵; in the Old Red Sandstone of the Cardiff district⁶; in the Millstone Grit of Yorkshire⁷; in the Bunter Pebble Bed of the West of England⁸; in the Keuper Waterstones of Leicestershire⁹; in the Upper Lias—Inferior Oolite sands of the West of England¹⁰; in the Kellaways Rock (Oxfordian) of Yorkshire etc.¹¹; in the Upper Kimmeridge Clay—Portland Sand of Buckinghamshire, etc.¹²; in the Thanet Sands,

Reading Beds and London Clay of the N.E. London basin¹³; in the Pliocene deposits of Cornwall¹⁴; in the later Tertiary deposits of the East of England¹⁵; in the Dartmoor detritals¹⁶.

Later Records. Cementstone Group, Lower Carboniferous, Northumberland¹⁷; Lower Greensand, East Kent¹⁸; Lower Greensand, Western Weald¹⁹.

Possible Sources of Derivation. Igneous and metamorphic rocks.

REMARKS.—It is sometimes found that two distinct varieties of muscovite occur in a sediment, one which floats, the other which sinks in bromoform (S.G. 2.9). In such circumstances very careful optical examination of the grains is desirable and may lead to the suspicion of leached biotite in the case of the heavier flakes.

References

- ¹ Author's observations.
- ² G. S. Sweeting, *Proc. Geol. Assoc.*, **38**, 1927, p. 553.
- ³ W. F. Fleet, *Geol. Mag.*, **62**, 1925, p. 98.
- ⁴ G. S. Sweeting, *loc. cit.*, p. 557.
- ⁵ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 512.
- ⁶ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 499.
- ⁷ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 263.
- ⁸ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 626.
- ⁹ T. O. Bosworth, Keuper Marls around Charnwood, *Leicester Lit. and Phil. Soc.*, 1913, p. 93.
- ¹⁰ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 252.
- ¹¹ Author's observations.
- ¹² E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 251.
- ¹³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1915, pp. 576, 578, 581.
- ¹⁴ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 358.
- ¹⁵ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 341.
- ¹⁶ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 46.
- ¹⁷ D. A. Robson, *Quart. Journ. Geol. Soc.*, **112**, 1956, p. 234.
- ¹⁸ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- ¹⁹ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

NACRITE

Chem. Comp. $8[\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4]$.

System. Monoclinic.

Habit. Tabular; often twinned (pseudo-hexagonal).

Structure. Crystalline.

Cleavage. Perfect \parallel (001), good \parallel (010) and (110).

Fracture. Irregular.

Hardness. 2.5–3.

Spec. Grav. $2.5 \pm$.

Lustre. Pearly, white.

Colour. Colourless.

Mag. Prop. Non-magnetic.

Elect. Prop. —

Opt. Prop. R.I. low, $\alpha = 1.557$ – 1.560 , $\beta = 1.562$, $\gamma = 1.563$ – 1.566 .

Birefringence weak, $\gamma - \alpha = 0.006$. Optically biaxial negative (may

be positive). Optic axial plane \perp (010). $Bxo = Z \perp$ (010). $2V = 40^\circ$ (neg. with $\rho > v$) or $2V = 90^\circ$ (pos. with $\rho < v$). $Z = b$. $X \wedge$ (001) 10° – 12° .

Characters in Sediments. In platy crystals or as aggregates. Similar to dickite (*q.v.* p. 94).

Occurrence. Suspected in certain English fireclays¹.

Possible Sources of Derivation. Quartz-veins; altered volcanic rocks; ore deposits. Alteration product of feldspar.

REMARKS.—A hydrothermal mineral of the kaolinite group and difficult of optical diagnosis without X-ray and other confirmatory tests (see Ch. III, p. 311). Extremely rare as at present recorded, but future investigations may be anticipated to disclose more frequent occurrences.

Reference

- ¹ J. W. Mellor, *Trans. Ceram. Soc.*, **16**, 1916, p. 83.

General References

- C. S. Ross and P. F. Kerr, *U.S. Geol. Surv., Prof. Paper* **165**, 1931.
G. W. Brindley and *ors.*, *X-ray Identification and Crystal Structures of Clay Minerals* (Miner. Soc., London), 1951, p. 49.
F. Smithson and G. Brown, *Miner. Mag.*, **31**, 1957, p. 389.

NEPHELINE

Chem. Comp. $8[\text{NaAlSiO}_4]$, with varying proportions of KAlSiO_4 and CaO in the natural mineral.

System. Hexagonal.

Habit. Tabular; occasionally prismatic.

Structure. Crystalline.

Cleavage. Poor \parallel (10 $\bar{1}$ 0) and (0001).

Fracture. Uneven.

Hardness. 5.5–6.

Spec. Grav. 2.55–2.65.

Lustre. Vitreous, pearly.

Colour. Colourless.

Mag. Prop. Non-magnetic.

Elect. Prop. --

Opt. Prop. R.I. low, ω 1.536–1.549, ϵ 1.532–1.544. Birefringence weak, $\omega - \epsilon$ 0.004–0.005. Optically uniaxial, negative (interference figure on (0001) usually rather blurred).

Characters in Sediments. Irregular shaped colourless or greyish-green grains.

Occurrence. In shore sands, S. Coast, Greenland¹.

Possible Sources of Derivation. Nepheline syenite; phonolite.

REMARKS.—A very rare detrital mineral, localized in recent deposits near appropriate parent-rocks. Rapidly alters to *cancrinite* and/or zeolites, e.g. *analcite* (p. 36), *sodalite* (p. 180).

Reference

- ¹ R. D. Crommelin, *Meddelelser om Grønland*, **113**, 1937.

NEPHRITE

(*Syn. JADE, Var. ACTINOLITE OR TREMOLITE, q.v. pp. 29, 197*)

NONTRONITE (CHLOROPAL)

(MONTMORILLONITE—BEIDELLITE SERIES)

Chem. Comp. (Fe, Al)₂O₃ . 2SiO₂ . 2H₂O. Also with Ca, Mg.

System. Monoclinic.

Habit. Prismatic, fibrous.

Structure. Crystalline, compact, earthy.

Cleavage. Perfect || (001).

Fracture. Irregular. Soft.

Hardness. 1.

Spec. Grav. 2.5.

Lustre. Pearly.

Colour. Green, olive green, yellow, orange. Translucent.

Mag. Prop. ?

Elect. Prop. ?

Opt. Prop. Variable with composition. R.I. moderate, $\alpha = 1.585$, $\beta = 1.593$, $\gamma = 1.608$. Birefringence moderate, $\gamma - \alpha = 0.023$. Optically biaxial, negative. $Bxa = X$ nearly (?) \perp (001). $Bxo = Z$ nearly (?) || elongation of fibres (*A. N. Winchell*). $X \perp$ cleavage. $2V = 26 \pm$. $2E = 42^\circ \pm$. When pleochroic, $X =$ pale yellow, $Y =$ olive green, $Z =$ yellow to bright green.

Characters in Sediments. Occurs as green, yellow or orange, prismatic grains of moderate R.I. and characteristic pleochroism (when developed). The optical properties are liable to vary with the degree of alteration which the parent mineral has undergone.

Occurrence. Ball clay, china clay, ordinary clay and Fuller's earth.

Possible Sources of Derivation. Alteration product of igneous rocks.

REMARKS.—Nontronite is a member of a series of hydrated ferrous-aluminous silicates characteristic of certain finely divided sediments such as clays. The series includes *montmorillonite* (p. 147) and *beidellite* (p. 59).

General References

B. C. Renick, Base Exchange in Ground Water by Silicates, as illustrated in Montana, *U.S. Geol. Surv., Water Supply Paper 520—D*, 1924.

W. Noll, Zur Kenntnis des Nontronits, *Chem. Erde*, 5, 1930, p. 373.

C. S. Ross and P. F. Kerr, The Clay Minerals and their Identity, *Journ. Sed. Pet.*, 1, 1931, p. 55.

G. W. Brindley, *X-ray Identification and Crystal Structures of Clay Minerals* (Miner. Soc., London), 1951.

R. E. Grim, *Clay Mineralogy*, (McGraw-Hill, New York), 1953.

OLIGOCLASE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. Ab_4An .

System. Triclinic.

Habit. Lamellar, massive. Crystals rare. Commonly twinned about (010) (Albite law); other types according to Carlsbad (c axis), pericline (b axis), Baveno (021) and Manebach (001) laws.

Structure. Crystalline.

Cleavage. Perfect \parallel (001), distinct \parallel (010), imperfect \parallel (110).

Fracture. Conchoidal, irregular.

Hardness. 6.

Spec. Grav. 2.64.

Lustre. Vitreous, pearly.

Colour. White, grey, green. Sometimes faintly iridescent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.539$, $\beta = 1.543$, $\gamma = 1.547$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial, negative. Optic axial plane nearly \parallel (010). $Bxa = X \wedge (001) = 1^\circ - 6^\circ$. $\wedge (010) = 1^\circ - 15^\circ$. $2V = 86^\circ$. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Detrital oligoclase appears from the records to be the most common member of the plagioclase feldspar group to be found in sediments. It seldom, if ever, presents crystal faces, irregular shaped grains being determined by (001) and (010) cleavages, usually with characteristic twin lamellae from which extinction angles may be measured. Identification is based on these, on lower R.I. than Canada balsam and on a tendency to show little or no alteration.

Occurrence. In the Torridonian Sandstone of the N.W. Highlands¹ and of S.E. Skye²; in the May Hill Sandstone (Silurian) of the Malvern district³; in the Old Red Sandstone of the West Midlands⁴; in the Millstone Grit of Yorkshire⁵; in the Northampton Ironstone⁶; in the later Tertiary deposits of East England⁷; in the Dartmoor detritals⁸; in the Mallee soil of Western Australia⁹.

Later Records. In St. Bees Sandstone, S. Cumberland and Furness¹⁰.

Possible Sources of Derivation. Igneous rocks, in particular acid types. Also gneiss and schist.

References

¹ J. J. H. Teall, *Geology of the N.W. Highlands, Mem. Geol. Surv. Scotland*, 1907, ch. xvi, p. 285.

² Author's observations.

³ G. S. Sweeting, *Proc. Geol. Assoc.*, **38**, 1927, p. 557.

⁴ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 499.

⁵ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 262.

⁶ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 385.

⁷ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 336.

⁸ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 46.

⁹ D. A. Carroll, *Journ. Roy. Soc. West Australia*, **20**, 1933-34, p. 100.

¹⁰ K. C. Dunham and W. C. C. Rose, *Proc. Geol. Assoc.*, **60**, 1949, p. 27.

General Reference

H. L. Alling, *The Mineralogy of the Feldspars, Journ. Geol.*, **21**, 1923, pp. 282, 353.

OLIVINE (CHRYSLITE)

(OLIVINE GROUP)

[Pl. 30A, B, between pp. 144-145]

Chem. Comp. $2(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$.*System.* Orthorhombic.*Habit.* Flattened prismatic crystals \parallel (100) or (010) with bipyramidal and basal terminations. Sometimes twinned on (011), rarely on (012).*Structure.* Crystalline, granular, massive.*Cleavage.* Poor \parallel (010) and (100).*Fracture.* Conchoidal.*Hardness.* 6.5-7.*Spec. Grav.* 3.27-3.37.*Lustre.* Vitreous, resinous.*Colour.* Green, olive green, dark green, brown.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. high, $\alpha = 1.653$, $\beta = 1.670$, $\gamma = 1.689$. Birefringence strong, $\gamma - \alpha = 0.036$. Optically biaxial, positive. Optic axial plane \parallel (001). $Bxa = Z - a \perp$ (100). $X = b$. $Y = c$. Straight extinction with prismatic grains. $2V = 88^\circ$. Non-pleochroic. Dispersion weak, $\rho < \nu$. With greater than 12% FeO, olivine is negative and the value for $2V$ exceeds 90° ; the R.I. is also higher, e.g. $\beta = 1.705$.*Characters in Sediments.* Usually occurs as irregularly shaped and much fractured grains, showing traces of decomposition to antigorite or chrysotile along one or more prominent cracks, frequently accentuated by hematite, limonite or goethite. Well preserved euhedra sometimes met with (Pl. 30). The normal colour tends to be bleached to a yellowish-green tint in sediments. Grains are often due to (010) or (100) cleavages and frequently show positive biaxial interference figure, with large optic axial angle. (N.B.—Most olivine is positive.) Note vivid polarization colours.*Occurrence.* In shore sands, Cape Verde Islands (beautiful euhedra)¹; in shore sands, Kynance Cove, S. Cornwall²; in the North Sea Drift and Upper Glacial Brick-earths, East Anglia²; in sands of the Northumberland coast⁴; in sand at Duntulm, Skye⁵.*Later Records.* In Pleistocene sands of the Netherlands⁶; in Beach Sand, Carbis Bay, Cornwall⁷; in monazite-bearing sands, Yellowknife geologic province, N.W. Territories, Canada⁸; in bottom deposits of the Northern Red Sea⁹.*Possible Sources of Derivation.* Basic and ultrabasic igneous rocks: gabbros, dolerites, peridotites, etc.**REMARKS.**—A comparatively rare detrital mineral, usually found in recent deposits (such as shore sands or dune sands) occurring in the vicinity of ultrabasic rock masses. See also *fayalite*, p. 106.*References*¹ G. M. Part's observations.² Author's observations.

- ² P. G. H. Boswell, *Proc. Geol. Assoc.*, **27**, 1916, p. 79.
⁴ L. Hawkes and J. A. Smythe, *Geol. Mag.*, **68**, 1931, p. 345.
⁵ F. Walker, *Trans. Edinburgh Geol. Soc.*, **12**, 1932, p. 321.
⁶ J. D. de Jong and W. P. de Roeper, *Geologie en Mijnbouw (N.W. Ser.)*, **18e Jaargang**, 1956, p. 61.
⁷ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.
⁸ R. E. Folinsbee, *Trans. Roy. Soc. Canada*, **49**, Ser. III, 1955, p. 7.
⁹ N. M. Shukri and R. A. Higazy, *Journ. Sed. Pet.*, **14**, 1944, p. 70.

OMPHACITE

(VARIETY OF DIOPSIDE, *q.v.* p. 96)

OPAL

Chem. Comp. $\text{SiO}_2 \cdot n\text{H}_2\text{O}$.

System. Amorphous.

Habit. Layers; botryoidal, stalactitic.

Structure. Massive, compact.

Cleavage. None.

Fracture. Conchoidal. Brittle.

Hardness. $6 \pm$.

Spec. Grav. $2.1 \pm$.

Lustre. Vitreous, porcellaneous, resinous.

Colour. White, milky. More rarely with brilliant play of colours (precious opal). Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $n = 1.406 \pm$. Isotropic; sometimes exhibits polarization colours due to strain.

Characters in Sediments. Opal is uncommon in sediments, but when identified under the microscope, it exhibits characteristic porcelain white, shapeless grains in reflected light, with R.I. much lower than Canada balsam, resulting in bold relief. Grains displaying colour are extremely rare. Independent determinations of S.G. and R.I. should always be made.

Occurrence. In the Suffolk Boxstones¹; in the Guedan (Middle Tertiary) formation of South-Western Texas, U.S.A.²; in Siliceous Shale (Miocene or Pliocene) of Southern California, U.S.A.³.

Later Records. In Liassic Ironstones, Cleveland, Yorkshire⁴; in N. Wales soils⁵.

Possible Sources of Derivation. Decomposed igneous rocks. Siliceous deposits.

REMARKS.—A rare, glass-clear form known as *hyalite* has been recorded from sediments.

References

- ¹ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 250.
² T. L. Bailey, *Univ. Texas Bull.* **2645**, 1926, p. 1.
³ R. D. Reed, *Journ. Geol.*, **36**, 1928, p. 342.
⁴ T. H. Whitehead and *ors.*, *Mem. Geol. Surv.*, 1952, p. 24.
⁵ F. Smithson, *Journ. Soil Sci.*, **9**, 1958, p. 148.

General References

- P. G. H. Boswell, Some Aspects of the Petrology of Sedimentary Rocks, *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 268.
 T. C. Wollaston, *Opal: The Gem of the Never Never* (Murby, London), 1928.
 F. Smithson, Silica Particles in Some British Soils, *Journ. Soil Sci.*, 7, 1956, p. 122.
 F. Smithson, Grass Opal in British Soils, *Journ. Soil Sci.*, 9, 1958, p. 148.

ORTHITE

(EPIDOTE GROUP)

(Syn. ALLANITE, *q.v.* p. 32)

ORTHOCLASE

(FELSPAR GROUP)

Chem. Comp. $K_2O \cdot Al_2O_3 \cdot 6SiO_2$.*System.* Monoclinic.*Habit.* Prismatic, often twinned according to the Carlsbad (001) or less commonly Baveno (021) laws.*Structure.* Crystalline.*Cleavage.* Perfect \parallel (001), good \parallel (010), imperfect \parallel (1 $\bar{1}$ 0).*Fracture.* Conchoidal.*Hardness.* 6.*Spec. Grav.* 2.56.*Lustre.* Vitreous.*Colour.* Colourless, grey or reddish-white.*Elect. Prop.* Non-conductor.*Mag. Prop.* Non-magnetic.

Opt. Prop. R.I. low, $\alpha = 1.518$, $\beta = 1.524$, $\gamma = 1.526$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial, negative. Optic axial plane \perp (010) $Bxa = X$ inclined at 85° to (001) or 5° (with a basal cleavage trace) in (010). $Bxo = Z \perp$ (010). Y or Z \approx b. (001) plates show straight extinction, (010) plates give extinction angle of 5° . $2V = 0^\circ - 70^\circ$. $2E = 0^\circ - 122^\circ$. Dispersion weak, $p > v$.

Characters in Sediments. Irregularly shaped grains flattened \parallel (001) are the usual types met with in the 'lighter' portions of clastic sediments. Secondary muscovite (sericite) or kaolinite clouding the grains is a common feature and in these types aggregate polarization will usually be noted. Rectangular grains showing definite Carlsbad twinning are sometimes met with; these are accordingly easy to diagnose. Distinction from quartz, where such twinning is absent, is sometimes a matter of difficulty, but R.I. test ($<$ Canada balsam) is usually positive. Inclusions common, quartz, mica, iron-ores, rutile and zircon being observed.

Occurrence. In the Torridonian Sandstones of the N.W. Highlands of Scotland¹; of S.E. Skye²; in the May Hill Sandstone (Silurian), Malvern district³; in the Old Red Sandstone of the West Midlands⁴ and of the Cardiff district⁵; in the Millstone Grit of Yorkshire⁶; in

the Upper Lias—Lower Inferior Oolite of the West of England⁷; in the Reading Beds (Eocene) of the N.E. London Basin⁸; in the Eocene of Haldon and the Oligocene sands of Bovey Tracey, Devonshire⁹; in the Pliocene of Cornwall⁹; in deposits of doubtful age, Lustleigh Cleave, Devonshire (in which the mineral is recorded as 'ultra-dominant')⁹; in the dune sands of South Wales¹⁰; in the Dartmoor detritals¹¹; in the Lappa Sand (soil deposit) of King Island, Tasmania¹².

Later Records. In St. Bees Sandstone, S. Cumberland and Furness¹³.
Possible Sources of Derivation. Acid igneous rocks, pegmatite veins.

REMARKS.—*Adularia* is a clear, colourless, orthoclase characterized by short prismatic crystals (110) terminated by (001) and (101). *Anorthoclase* is the triclinic, soda-potash feldspar (p. 45). *Perthite* and *microperthite* are names given to regular intergrowths of orthoclase (or microcline, p. 143) and albite (p. 31). *Sanidine* is a tabular, glassy type (010), or elongated || with (001) termination, found chiefly in sediments derived from volcanic rocks.

References

- ¹ J. J. H. Teall, Geology of N.W. Highlands, *Mem. Geol. Surv., Scotland*, 1907, p. 278.
- ² Author's observations.
- ³ G. S. Sweeting, *Proc. Geol. Assoc.*, **38**, 1927, p. 557.
- ⁴ W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 512.
- ⁵ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 511.
- ⁶ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 262.
- ⁷ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 258.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1915, p. 579 and table iv.
- ⁹ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ¹⁰ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 324.
- ¹¹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 46.
- ¹² D. A. Carroll, *Journ. Roy. Soc., West. Australia*, **20**, 1933–34, p. 99.
- ¹³ K. C. Dunham and W. C. C. Rose, *Proc. Geol. Assoc.*, **60**, 1949, p. 25.

General Reference

H. L. Alling, The Mineralogy of the Feldspars, *Journ. Geol.*, **31**, 1923, pp. 282, 353. See also Bibliography, W. Mackie (p. 662).

OTTRELITE

(CHLORITOID—OTTRELITE GROUP)

Chem. Comp. (Fe, Mn)O . Al₂O₃ . 3SiO₂ . H₂O.

System. Monoclinic (pseudo-hexagonal) or triclinic.

Habit. Similar to mica. Curved crystals.

Structure. Crystalline, radiating aggregates, laminated.

Cleavage. Perfect || (001).

Fracture. Irregular.

Hardness. 7.

Spec. Grav. 3.3.

Lustre. Pearly.

Colour. Grey, green.

Mag. Prop. Weakly magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\beta = 1.73$. Birefringence moderate, $\gamma - \alpha = 0.010$. Optically biaxial, positive. Optic axial plane nearly $\parallel (010)$. $Bxa = Z \wedge 3^\circ - 30^\circ \perp (001)$. $Y \wedge b = 0^\circ \pm$. Optic axial angle variable. Pleochroism $X = \text{olive green}$, $Y = \text{blue}$, $Z = \text{yellow-green}$. Distinct horizontal dispersion, $\rho > \nu$.

Characters in Sediments. A much rarer occurrence in detrital sediments than its closely allied species *chloritoid* (p. 79). Characterized by micaceous habit, colour, high R.I., biaxial positive character and distinctive pleochroism. Frequently contains carbonaceous inclusions symmetrically arranged; also quartz, iron ores.

Occurrence. In the Limburg Loess.¹

Possible Sources of Derivation. Crystalline schists and phyllites.

REMARKS.—See also *chloritoid*, p. 79.

Reference

¹ J. H. Druif, Over het ontstaan der Limburgsche Löss in verband met haar mineralogische Samenstelling, *Utrecht*, 1927.

General Reference

H. D. Hedberg, *Joarn. Paleont.*, 2, 1928, p. 32.

PALLADIUM

Chem. Comp. Pd (usually alloyed with Pt and Ir).

System. Isometric; hexoctahedral.

Habit. Seldom crystallized, normally as grains.

Structure. Granular.

Cleavage. None.

Fracture. Difficult; ductile and malleable.

Hardness. 4.5–5.

Spec. Grav. 11.9.

Lustre. Metallic.

Colour. Steel-grey, whitish grey.

Mag. Prop. Non-magnetic.

Elect. Prop. —

Opt. Prop. Opaque.

Characters in Sediments. As irregularly shaped granules or platy grains.

Occurrence. In gold and diamond washings, British Guiana¹; in Potaro River alluvials, British Guiana²; in alluvials at Itabira, Minas Geraes, Brazil³.

Possible Sources of Derivation. Ultrabasic igneous rocks.

REMARKS.—A rare mineral. Confirm by chemical and spectrographic tests. *Alloppalladium*, a hexagonal (? rhombohedral) form of palladium associated with gold and platinum, has been described from the Hartz Mountains; also from gold and diamond deposits in British Guiana.

References

- ¹ L. J. Spencer, *Miner. Mag.*, **20**, 1925, p. 217.
² J. B. Harrison and C. L. C. Bourne, *Miner. Mag.*, **21**, 1926, p. 4.
³ J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), **1**, 1944, p. 110.

PENNINITE

(CHLORITE GROUP)

Chem. Comp. $5(\text{Mg, Fe})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$.*System.* Monoclinic.*Habit.* Lamellar, platy (001). Twinned on (001) and (110).*Structure.* Crystalline, granular, scaly, radiating.*Cleavage.* Perfect \parallel (001), flexible flakes.*Fracture.* None.*Hardness.* 2.5.*Spec. Grav.* $2.7 \pm$.*Lustre.* Pearly.*Colour.* Green. Translucent to opaque.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.576$, $\beta = 1.576$, $\gamma = 1.579$. Birefringence weak, $\gamma - \alpha = 0.003$. Optically biaxial, positive. Optic axial plane \parallel (010). $Bxa \perp Z \perp$ (001). $Y \perp b$. Optic axial angle small, $2E = 0^\circ +$. Dispersion strong, $\rho < \nu$. Some varieties present pseudo-hexagonal characteristics with uniaxial positive interference figure; more rarely uniaxial negative. A biaxial negative form is also known. Most grains exhibit abnormal 'ultra-blue' interference tints. Pleochroism: $(+)X = \text{green} \rightarrow Y = \text{green} \rightarrow Z = \text{yellow-green}$; $(-)X = \text{yellow-green} \leftarrow Y = \text{green} \leftarrow Z = \text{green}$.

Characters in Sediments. Detrital penninite *per se* is rare (see under chlorite group, p. 78). When identified it is usually in the form of (001) flakes or 'shreds', distinguished by colour, low R.I. positive (or negative) interference figure and 'ultra-blue' polarization tint.

Occurrence. In the Millstone Grit, Huddersfield¹; in the Eocene Tejon formation, California, U.S.A.².

Possible Sources of Derivation. Alteration product of ferromagnesian minerals. Decomposed igneous rocks.

REMARKS.— See also *antigorite* (p. 46), *clinochlore* (p. 84) and *delessite* (p. 92).

References

- ¹ D. A. Wray and S. Melmore, *Proc. Yorks. Geol. Soc.*, **22**, 1931, p. 31.
² A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, **15**, No. 7, 1925, p. 159.

PERICLASE

Chem. Comp. MgO .*System.* Isometric.*Habit.* Cubes, octahedra.

Structure. Crystalline, granular.

Cleavage. Perfect \parallel (100), poor \parallel (111).

Fracture. Uneven.

Hardness. 5.

Spec. Grav. 3.6.

Lustre. Vitreous.

Colour. Colourless, grey, yellow, dark green, transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $n = 1.736$, optically isotropic.

Characters in Sediments. Occurs as colourless, yellow or dark green grains characterized by high R.I. and perfect cubic cleavage. It is a very rare detrital mineral to be anticipated only in favourable associations, e.g. forsterite, magnesite, spinel. Periclase is unstable, readily changing to brucite ($\text{MgO} \cdot \text{H}_2\text{O}$), hydromagnesite, etc.

Possible Sources of Derivation. Contact-altered magnesium limestones.

REMARKS.—A rare species but to be anticipated in deposits derived from dolomitic limestone and related marble.

PEROVSKITE

[Pl. 31A, between pp. 144–145]

Chem. Comp. CaTiO_3 .

System. Pseudoisometric; ? monoclinic or orthorhombic.

Habit. Cubic, more rarely octahedra. Cubic faces striated \parallel (001).

Sometimes twinned, interpenetration, on (111): complex.

Structure. Crystalline.

Cleavage. Imperfect \parallel (001), poor \parallel (100).

Fracture. Uneven to subconchoidal. Brittle.

Hardness. 5.5.

Spec. Grav. $4.01 \pm$.

Lustre. Adamantine, metallic; sometimes dull.

Colour. Black, grey-black, brown-black. Opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. —

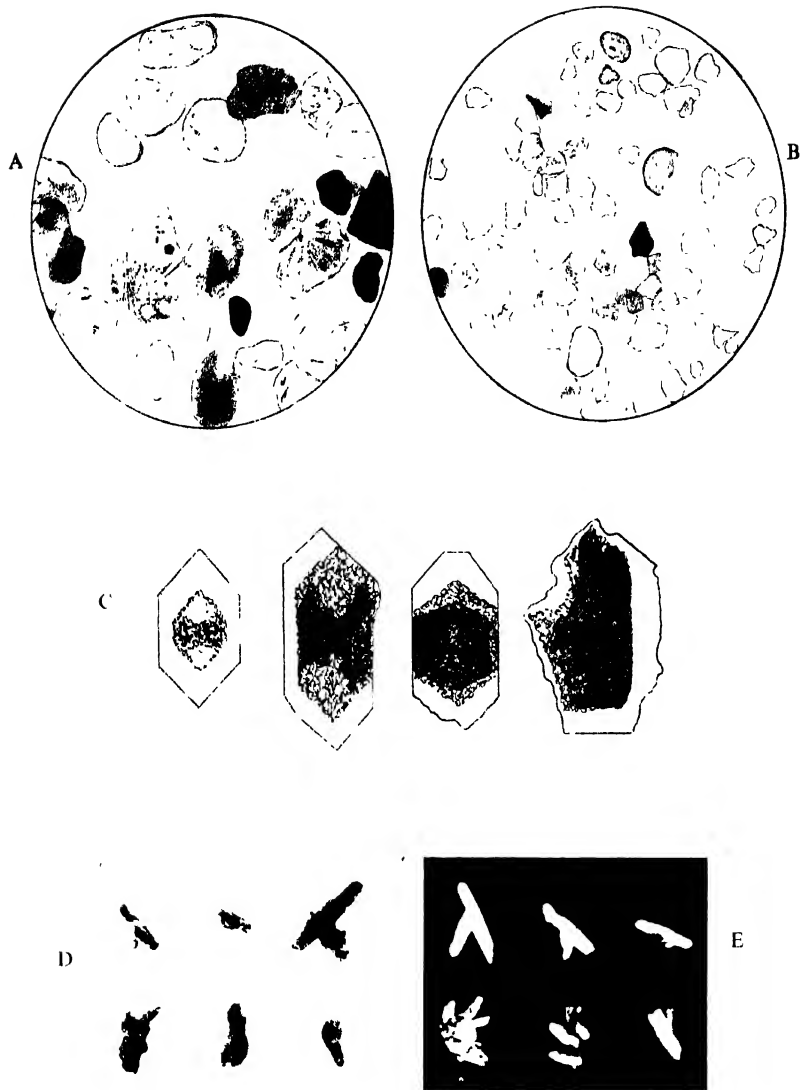
Opt. Prop. Isotropic; occasionally birefringent in thin crystal edges.

R.I. very high, $n = 2.30\text{--}2.37$. When birefringent, optically biaxial, positive. $Z = a$, $Y = b$. $2V = 90^\circ \pm$. $Z \wedge c$ (or a) 45° in monoclinic form. Pleochroism weak, $Z > X$.

Characters in Sediments. As black, opaque square-shaped grains with dull lustre. Some very small grains reveal translucent brown margins from which optical properties may be checked.

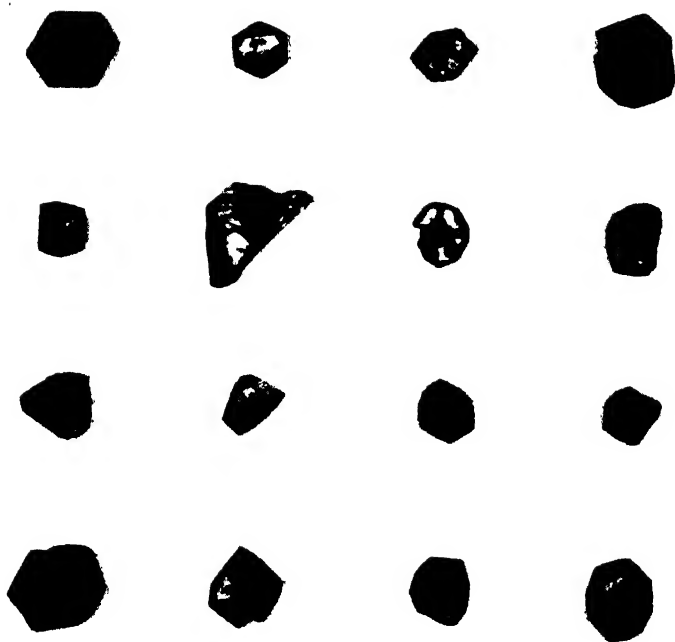
Occurrence. In crystalline limestone at Vogtsburg and Schelingen, Kaiserstuhl, Baden, Germany¹; in diamondiferous alluvial deposits, Bahia, Brazil².

Possible Sources of Derivation. Basic alkaline igneous rocks and pegmatites; metamorphosed limestone; schist.

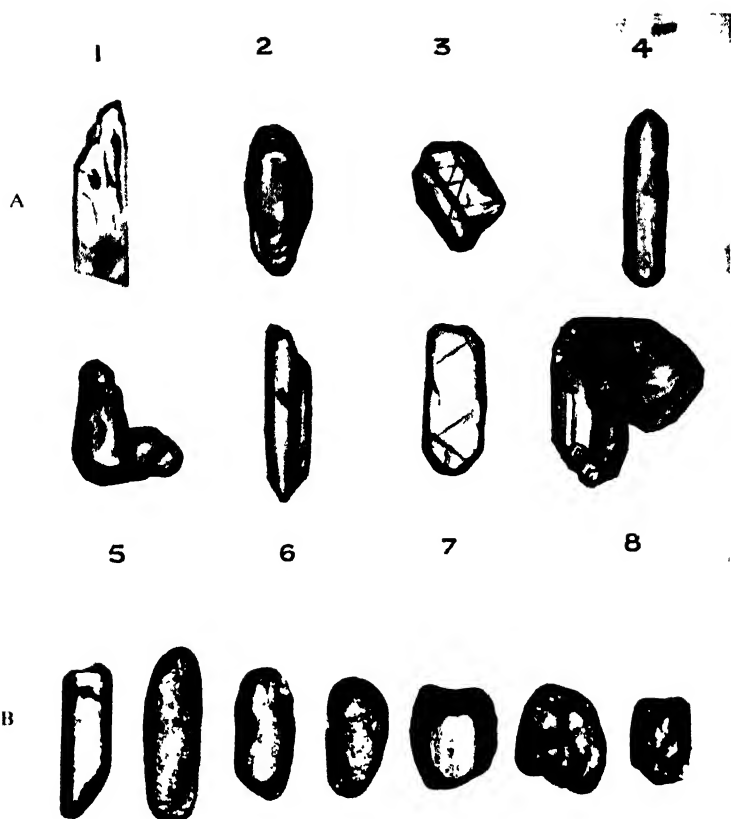


A-E. QUARTZ.

- A Blown Sand, Newgale, Pembrokeshire [x 25] (Note degree of rounding)
 B Tunbridge Wells Sand, Eridge, Sussex [x15]
 C Euhedra etc, extracted from Carboniferous Limestone, Halkyn, N. Wales [x 35]
 D "Dogger" Sands, Md Jurassic, Yorkshire [x 38]
 E "Dogger" Sands, Md Jurassic, Yorkshire *Polarised light* [x 51]



ROMITI.
Fluvial Sands, Tripuhy, Minas Geraes, Brazil [x 40]



A, B RUTILI

- A 1, 6, 7 Lower Greensand, N.W. Wiltshire [x 70]
- A 2, 4 Tunbridge Wells Sand, Kent [x 60]
- A 5 Genticulate twin, Tunbridge Wells Sand, Kent [x 100]
- A 8 Genticulate twin, Recent Sands, Ceylon [x 70]
- B Tertiary, New South Wales [x 57]

PHLOGOPITE

(MICA GROUP)

Chem. Comp. $2K_2O \cdot 10(Mg, Fe)O \cdot 3Al_2O_3 \cdot 12SiO_2 \cdot 3H_2O$.*System.* Monoclinic (pseudo-hexagonal).*Habit.* Tabular, six-sided prisms with well developed basal planes.

Twinned on (110) in thin (001) laminae.

Structure. Lamellar.*Cleavage.* Perfect \parallel (001).*Fracture.* Uneven.*Hardness.* 3-4.*Spec. Grav.* 2.8-3.3.*Lustre.* Pearly, submetallic on cleavage planes.*Colour.* Brown.*Mag. Prop.* Moderately magnetic.*Elect. Prop.* Moderate conductor.*Opt. Prop.* R.I. low, $\alpha = 1.551$, $\beta = 1.598$, $\gamma = 1.598$. Birefringence strong, $\gamma - \alpha = 0.047$. Optically biaxial, negative. Optic axial plane \parallel (010). $Bxa = X$ nearly \perp (001). $2V = 3^\circ$ or zero. $2E = 5^\circ - 70^\circ$. Pleochroism: $X =$ colourless $< Y =$ brownish-yellow $< Z =$ brownish-yellow; or with increase of iron colours may be darker and $X < Z < Y$. Dispersion weak, $\rho < \nu$.*Characters in Sediments.* Usually occurs in shapeless grains or flakes of brown or copper-brown colour characterized by higher R.I. than ordinary biotite, by distinctive pleochroism and tendency to acicular inclusions sometimes orientated along lines traversing each other about 60° (asterism). Inclusions are usually iron ores, rutile, tourmaline. Pleochroic halos round inclusions are most uncommon in phlogopite, by contrast with biotite.*Occurrence.* In the Thanet Beds of the North-Eastern part of the London Basin¹.*Possible Sources of Derivation.* Contact-metamorphosed limestone and dolomite; dedolomitized impure dolomite. Rare in igneous rocks.*Reference*¹ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 536.

PHOSPHORITE

(See Apatite, p. 47, also p. 273)

PICOTITE

(SPINEL GROUP)

Chem. Comp. $(Mg, Fe)O, (Al, Fe, Cr)_2O_3$.*System.* Isometric.*Habit.* Octahedral, irregular, granular.*Structure.* Crystalline.*Fracture.* Conchoidal.*Hardness.* 8.

Spec. Grav. 4.08.

Lustre. Vitreous to dull metallic.

Colour. 'Coffee-brown', yellowish-brown or greenish-brown. Translucent, sometimes opaque.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. R.I. very high, $n = 2.05 \pm$. Opaque or exhibiting a greenish-brown translucency, when isotropism is noted.

Characters in Sediments. Usually occurring as rolled octahedral grains of dark but characteristic 'coffee' colour, much resembling chromite, from which it is not always easily distinguishable microscopically.

Occurrence. Reading Beds (Lower Eocene) of the London Basin¹; in the shore sands of Mullion Cove and elsewhere along the West coast of the Lizard, Cornwall (proximity to serpentine masses)².

Later Records. In Carboniferous rocks, Stranraer, Wigtownshire³.

Possible Sources of Derivation. Similar to chromite: basic and ultra-basic igneous rocks, especially serpentine rocks; crystalline schists.

REMARKS.--As might be expected, picotite as a detrital mineral is of very restricted occurrence: it tends to be confined to localized (geologically) recent deposits.

References

¹ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1915, p. 578.

² Author's observations.

³ J. G. C. M. Fuller, *Proc. Geol. Assoc.*, **69**, 1958, p. 166.

General Reference

D. Carroll, *Bull. Amer. Assoc. Pet. Geol.*, **24**, 1940, p. 636, and *ref. there cited*.

PIEDMONTITE

(EPIDÓTE GROUP)

Chem. Comp. $4(\text{Ca}, \text{Mn})\text{O} \cdot 3(\text{Al}, \text{Fe}, \text{Mn})_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Like epidote (p. 102); elongated || b. May be twinned about (100).

Structure. Crystalline.

Cleavage. Perfect || (001).

Fracture. Uneven.

Hardness. 6.5.

Spec. Grav. 3.45-3.5.

Lustre. Vitreous, resinous.

Colour. Reddish-brown, black. Translucent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 1.750$, $\beta = 1.782$, $\gamma = 1.832$. Birefringence strong, $\gamma - \alpha = 0.082$. Optically biaxial, positive. Optic axial plane || (010). $Bxa - X = 7^\circ \pm$. $Bxo - Z = (001)$ cleavage

= $32^\circ \pm$. $Y = b$. $2V = 55^\circ\text{--}80^\circ$. Inclined and strong dispersion, $\rho > \nu$. Pleochroism: $X = \text{yellow or orange-yellow} > Y = \text{violet or pink} > Z = \text{red}$. Biaxial negative forms also known with larger axial angle (near 90°).

Characters in Sediments. Grains are usually quite irregular in shape, of a strong reddish-brown to blackish-brown colour, characterized by high R.I., birefringence and distinctive pleochroism. The mineral is generally positive, thus differing from epidote.

Occurrence. In Pliocene sands from borings at Fisrenco, Italy¹; in shore sands of the Adriatic²; in the Limburg Loess³; in soils of the U.S.A.⁴; in shore sands, S. coast Greenland⁵.

Later Records. In sands of Hoggar district, Central Sahara⁶.

Possible Sources of Derivation. Metamorphic rocks, schist, gneiss. Acid volcanic rocks.

REMARKS.—Confirmatory test for manganese is desirable where possible.

References

- ¹ E. Repossi, *Atti R. Accad. Sci. Torino*, **63**, 1928, p. 223.
- ² E. Artini, *Rend. R. Ist. lomb.*, **29**, 1896, p. 800.
- ³ J. H. Druif, Over het ontstaan der Limburgsche Löss in verband met haar mineralogische Samenstelling, *Utrecht*, 1927.
- ⁴ W. H. Fry, *Econ. Geol.* (Letter), **10**, 1915, p. 292.
- ⁵ R. D. Crompton, *Meddelelser om Grønland*, **113**, 1937.
- ⁶ H. M. E. Schurmann, *Geol. en Mijnbouw*, **5**, Nw. Serie, 18e Jaargang, 1956, p. 163.

PLAGIOCLASE FELSPAR

See Varieties:

Albite (p. 31).	Bytownite (p. 67).
Andesine (p. 40).	Labradorite (p. 134).
Anorthite (p. 44).	Oligoclase (p. 151).

PLATINUM

[Pl. 32, between pp. 144-145]

Chem. Comp. Pt.

System. Isometric; hexoctahedral.

Habit. Crystals rare, often distorted. Usually as grains or scales.

Structure. Often structureless; sometimes traces of scale-like lamination; granular.

Cleavage. None.

Fracture. Rare. Soft, malleable and ductile.

Hardness. 4-4.5.

Spec. Grav. 14-19 (native); 21-22 (chemically pure).

Lustre. Metallic; dull silver-grey.

Colour. White, aluminium-grey. Opaque.

Mag. Prop. Non-magnetic except in Fe-bearing variety.

Elect. Prop. Good conductor.

Opt. Prop. In polished section, white, isotropic.

Characters in Sediments. As worn, flattened polygonal plates or irregular granules of characteristic aluminium-grey colour and rough texture.

Occurrence. In Co. Wicklow, Ireland¹; in Ivalo River sands, N. Finland²; in Rhine sand³; in deposits of Tura and Iss rivers, Perm Province, E. Urals, U.S.S.R.⁴; in alluvial deposits, R. Pinto, Papayan, Cauca, Colombia⁵; in alluvial deposits, north of serpentine mass, Lizard district, Cornwall⁶.

Possible Sources of Derivation. Basic and ultrabasic igneous rocks (dunite); more rarely in nickel-copper sulphide ores and quartz veins.

REMARKS.—Always to be looked for in recent deposits derived from olivine-rich rocks, *e.g.* dunite, peridotite, serpentine.

References

¹⁻⁵ J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, p. 108.

⁶ E. H. Davidson, *Mining Mag.*, 33, 1925, pp. 89–90.

General References

F. W. Clarke, Data of Geochemistry, *U.S.G.S., Bull.* 770, 1924, p. 720, and refs. cited.

C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 412.

PSEUDOBROOKITE

Chem. Comp. Fe_2TiO_5 .

System. Orthorhombic; dipyramidal.

Habit. Tabular \parallel (100), elongated with (001); prismatic, sometimes striated.

Structure. Crystalline.

Cleavage. Distinct \parallel (010).

Fracture. Uneven.

Hardness. 6.

Spec. Grav. 4.3–4.4.

Lustre. Adamantine, metallic.

Colour. Dark reddish-brown to brownish black.

Mag. Prop. Weakly magnetic.

Elect. Prop. --

Opt. Prop. R.I. very high, $\alpha = 2.38$, $\beta = 2.39$, $\gamma = 2.42$. Birefringence strong, $\gamma - \alpha = 0.04$. Optically biaxial, positive. $Z = a$, $X = c$. $2V = 50 \pm$. $\rho < v$. Weakly pleochroic in reddish brown crystals, $X < Y < Z$. Straight extinction.

Characters in Sediments. To be anticipated in flattened prismatic grains of characteristic colour and optical properties. On one well developed crystal 'the following forms were found (orientation Koch, unit Pauling): (010), (100), (110), (210), (101) and (111). Extreme refraction, parallel extinction, pleochroic in brown with dark

red-brown and X light red-brown. Optic axial angle very large, axial dispersion $\rho < \nu$ with reference to Z'^1 .

Occurrence. In sands of Hoggar district, Central Sahara².

Possible Sources of Derivation. Volcanic igneous rocks as a pneumatolytic or fumarolic product.

REMARKS.—Pseudobrookite can occur as oriented upon hematite and magnetite (Dana, *Gen. Ref.* below, p. 737). Differs from brookite in form, larger optic axial angle and far less dispersion. Very rare as detrital.

References

¹ W. P. de Roever, personal communication to the author (1958) re ref. 2 below.

² H. M. E. Schurman, *Geol. en Mijnbouw*, 5, Nw. Serie, 18e Jaargang, 1956, p. 163.

General Reference

J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, p. 738 and refs. cited.

PSILOMELANE

Chem. Comp. Hydrated oxide of manganese. Ba and K sometimes present.

System. Amorphous.

Habit. Massive.

Structure. Botryoidal, reniform, stalactitic.

Cleavage. None.

Fracture. Smooth.

Hardness. 5–6.

Spec. Grav. 4.2.

Lustre. Sub-metallic, dull.

Colour. Grey, black.

Mag, Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. Opaque.

Characters in Sediments. Irregular, steel-grey grains with smooth surface and dull metallic lustre. Difficult of diagnosis by microscopical means alone.

Occurrence. Tertiary and Pleistocene deposits of Colorado County, Texas, U.S.A.¹.

Possible Sources of Derivation. Sedimentary rocks as result of direct precipitation. Residual deposits. Manganese-bearing minerals and silicates. Lode minerals.

REMARKS.—Chemical test for Mn always desirable. Comparatively rare mineral in sediments and particularly in British sedimentary rocks of pre-Pleistocene age.

Reference

¹ T. L. Bailey, *Univ. Texas Bull.*, 2333, 1923.

General Reference

P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, **13**, 1923, p. 268.

PUMPELLYITE

[Pl. 31B, *between pp.* 144–145]

Chem. Comp. $\text{Ca}_4(\text{Al}, \text{Mg}, \text{Fe})_6\text{Si}_6\text{O}_{23}(\text{OH})_3 \cdot 2\text{H}_2\text{O}$ or
 $(\text{Ca}, \text{Mg}, \text{Fe})_6 \text{Al}_6\text{Si}_7\text{O}_{29} \cdot 4\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Flattened $\parallel (100)$; sometimes fibrous and curvilinear. Twinning on (001), sometimes on (100); cruciform twins recorded.

Structure. Crystalline.

Cleavage. Perfect $\parallel (100)$, less perfect $\parallel (001)$.

Fracture. Uneven.

Hardness. 5.5.

Spec. Grav. 3.18–3.2.

Lustre. Vitreous or dull.

Colour. Bluish-green, brown.

Mag. Prop. ---

Elect. Prop.

Opt. Prop. R.I. high, variable: $\alpha = 1.698$, $\beta = 1.706$, $\gamma = 1.720$. Birefringence moderate, $\gamma - \alpha = 0.022$. Optically biaxial, positive. Optic axial plane (010). $2V = 30^\circ - 80^\circ$. Dispersion strong, $\rho < \nu$. Pleochroism of varying intensity, maximum absorption \parallel elongation, X and Z - colourless, Y = bluish green, pale green or brownish yellow. $Y = b$. $X \wedge a = 59^\circ$. Straight extinction in longitudinal crystals.

Characters in Sediments. Dark or light green to colourless aggregates or fibrous developments; as crystalline grains with variable optical properties; to be carefully confirmed.

Occurrence. In Quaternary deposits of the Netherlands¹. (See general references below for other occurrences.)

Possible Sources of Derivation. Low grade metamorphic spilites, diabase; tuffaceous greywackes; glaucophane schist; iron ores.

REMARKS. A mineral of wide geographical and environmental range, much commoner than originally recognized. According to C. H. Edelman '... the mineral designated by the name of chloropite, now identified as pumpellyite, forms 1 to 4% of the heavy translucent minerals in samples from more than a hundred different localities'. Edelman also described some grains found in samples from Belgium, France and Denmark. (Ref. 1 below, p. 164.)

Reference

¹ J. H. Laugenberg and W. P. de Roever, *Geol. en Mijnbouw (N.W. Ser.)* 17e Jaargang, 1955, p. 163.

General References

C. H. Edelman, Petrologische provinces in het Nederlandsche Kwart in, Univ. Amsterdam. Thesis. Amsterdam (Centen's Uitgevers Maatschappij), 1933.

- H. W. Quitzow, Pumpellyit, ein häufiges Hydrothermal-und Sekundär-mineral in basischen Gesteinen, *Zentralbl. Min.*, v. 1936, A, pp. 39–46.
 D. S. Coombs, The Pumpellyite Mineral Series, *Miner. Mag.*, **30**, 1953, pp. 113–135.
 H. Struwe, Data on the Mineralogy and Petrology of the Dolomitic-Bearing Northern Contact Zone of the Querigut Granite, French Pyrenees. Thesis, Univ. of Leiden (E.ljds N.V.—Leiden), 1958, p. 283. See also Leidse Heologische Mededelingen, vol. 22.

PYRITE

[Pl. 33A, B, *between pp. 160–161*]

Chem. Comp. FeS₂.

System. Isometric.

Habit. Cubic, dodecahedral, 'pyritohedral' and combinations of different forms. Often twinned (interpenetrant); cubic faces frequently striated || edge (100) (210).

Structure. Crystalline, massive.

Cleavage. Poor || (100) and (111).

Fracture. Conchoidal, uneven; brittle.

Hardness. 6–6.5.

Spec. Grav. 4.8–5.1.

Lustre. Metallic, splendid.

Colour. Brass-yellow, sometimes tarnished.

Mag. Prop. Non-magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque.

Characters in Sediments. Commonly occurs in well crystallized dodecahedra or 'pyritohedra', the latter often in complex interpenetration. Other forms are nodular, botryoidal; sometimes masses of minute crystals unite to produce aggregates of fantastic appearance, especially when the mineral is intimately associated with lignite, as in clays, or with asphaltic limestones. The brass-yellow colour by oblique dark ground and creamy-white colour by vertical illuminations, are very characteristic, as is also the tarnish (a dull blackish-brown veneer) due to alteration, probably to limonite. Simple cubic grains are rare.

Occurrence. In most argillaceous rocks, especially Jurassic and Cretaceous clays in England. Prolific in many of the Cambrian, Ordovician and Silurian shales of Wales and the Welsh borderland¹; in the Devonian and Culm Beds of the Torquay district²; in the Permian rocks of the Torquay Promontory³; in the Northampton Ironstone⁴; in the Fairlight Clays of Fairlight, Sussex⁵; in the Wadhurst Clay (Wealden) generally⁶; in the Weald Clay, Atherfield Clay, Sandgate Beds (Lower Greensand), Woolwich and Reading loams, London Clay of the Croydon Regional Survey area (Surrey etc.)⁷; in the Dartmoor detritals⁸.

Later Records. In Lower Carboniferous, Anglesey and Caernarvonshire⁹; in Oil Shale Group, Lower Carboniferous, Scotland¹⁰; in Liassic Ironstones, Cleveland, Yorkshire¹¹; in Hythe Beds, Tilburstow

Hill, Surrey¹²; in Fuller's Earth, Western Weald¹³; in Lower Greensand, E. Kent¹⁴.

Possible Sources of Derivation. Igneous and sedimentary rocks, metaliferous veins; chiefly authigenic.

REMARKS.—Pyrite is more common in detrital sediments than its isomer marcasite (p. 141) except in certain local cases. It may be removed from residues (if necessary) by boiling with weak HNO₃, or a better method is to use 100 vol. hydrogen peroxide, which has the advantage of not attacking many minerals which are liable to reaction with acid.

References

- ¹ Author's observations.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 137.
- ³ W. G. Shannon, *Proc. Geol. Assoc.*, **38**, 1927, p. 133.
- ⁴ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 380.
- ⁵ H. B. Milner, *Proc. Geol. Assoc.*, **36**, 1925, p. 315.
- ⁶ Author's observations.
- ⁷ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, p. 82.
- ⁸ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 35.
- ⁹ F. Smithson, *Geol. Mag.*, **91**, 1954, p. 180.
- ¹⁰ L. G. Love, *Quart. Journ. Geol. Soc.*, **113**, 1957, p. 429.
- ¹¹ T. H. Whitehead and ors., *Mem. Geol. Surv.*, 1952, p. 23.
- ¹² W. E. Smith, *Proc. Geol. Assoc.*, **68**, 1957, p. 45.
- ¹³ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
- ¹⁴ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.

General References

- F. A. Bannister, The Distinction of Pyrite from Marcasite, etc., *Miner. Mag.*, **23**, 1932, p. 179.
- F. Smithson, The Habit of Pyrite in some Sedimentary Rocks, *Miner. Mag.*, **31**, 1956, p. 314 and Pl. XI.

PYROLUSITE

Chem. Comp. MnO₂.

System. Amorphous (?Orthorhombic).

Habit. Probably pseudomorphous after manganite (Mn₂O₃ · H₂O).

Structure. Normally amorphous, massive.

Cleavage. None.

Fracture. Splintery, uneven.

Hardness. 2–2.5.

Spec. Grav. 4.75.

Lustre. Metallic, dull.

Colour. Purplish-black.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. Opaque.

Characters in Sediments. Usually occurs in the form of irregular purplish or dead black grains, void of all crystalline structure. P. G. H. Boswell thus notes one occurrence: 'It has a flat irregular and angular form, is dull black by reflected light, but sometimes shows striations or flutings characteristic of the mineral'.

Occurrence. In the Fairlight Clays (Wealden) of Sussex¹; in the Chalk of Surrey etc.²; in the Thanet Beds (Eocene) of the N.E. London Basin³.

Possible Sources of Derivation. Of secondary origin, derived by oxidation of manganese present in various rocks; metalliferous veins; organic.

REMARKS.—Pyrolusite occurs chiefly as an authigenic constituent of detrital sediments, also frequently as dendritic aggregates on the joint planes of sediments and on individual pebbles. Should always be confirmed by chemical test: borax bead attains a violet-red colour in oxidizing flame; fused with Na_2CO_3 yields a bluish-green mass.

References

¹ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 312.

² G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.

³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 577.

PYROPE

(GARNET GROUP)

Chem. Comp. $3\text{MgO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$.

System. Isometric.

Habit. Dodecahedral (110), trapezohedral (211) etc., but rarely crystallized.

Structure. Fragmentary.

Cleavage. None.

Fracture. Conchoidal.

Hardness. 7.

Spec. Grav. 3.51.

Lustre. Vitreous.

Colour. Red, crimson, purplish-red. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $n = 1.705$. Optically isotropic: seldom anomalous in this respect.

Characters in Sediments. Pyrope occurs as either rolled or shapeless, angular grains of deep red or purple-red colour. Tendency to alteration to a green decomposition product known as 'kelyphite', an intimate intergrowth of fibrous amphibole and felspar; also exhibits alteration to chlorite minerals.

Occurrence. In the Red Crag Ironstone of Netley Heath, Surrey¹; in the Black Sands of Idaho, U.S.A.²; in alluvium and gravels of Arizona and Utah, U.S.A.³.

Possible Sources of Derivation. Ultrabasic igneous rocks: almost exclusively confined to serpentine and peridotite.

REMARKS.—A well-known source of pyrope is the famous 'blue ground' (serpentine breccia), diamondiferous deposits of Kimberley, South Africa.

References

¹ P. G. H. Boswell, in H. G. Dines and F. H. Edmunds, *The Geology of the Country around Aldershot and Guildford*, *Mem. Geol. Surv., Great Britain*, 1929, p. 114.

² E. V. Shannon, *Proc. U.S. National Mus.*, **60**, 1921, p. 1.

³ H. E. Gregory, *Econ. Geol.*, **11**, 1916, p. 223.

PYROPHYLLITE

(KAOLINITE GROUP)

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic? (Pseudohexagonal).

Habit. Tabular, lamellar \parallel (001), bladed, fibrous.

Structure. Crystalline.

Cleavage. Perfect \parallel (001).

Fracture. Uneven.

Hardness. 1-1.5.

Spec. Grav. 2.6-2.9.

Lustre. Vitreous, pearly.

Colour. Colourless, white, grey, pale green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.552$, $\beta = 1.588$, $\gamma = 1.600$. Birefringence strong. $\gamma - \alpha = 0.048$. Optically biaxial, negative. Optic axial plane \perp (001). $Bxa = X = c \perp$ (001). $Bxo = Z \parallel$ elongation of bladed or fibrous grains. $2V = 57^\circ$. $2E = 98^\circ$. Dispersion weak, $\rho > \nu$.

Characters in Sediments. Diagnosed chiefly by its form usually (001) flakes, or fibres and by its strong birefringence. It has a larger optic axial angle than muscovite with which it may be confused if uncoloured.

Occurrence. In certain soils of the United States^{1,2}.

Possible Sources of Derivation. Metamorphic rocks, schist.

References

¹ W. H. Fry, *Econ. Geol.* (Letter), **10**, 1915, p. 292.

² W. J. McCaughey and W. H. Fry in W. O. Robinson, *U.S. Dept. Agric., Bull.* **122**, 1914.

PYRRHOTITE

Chem. Comp. $\text{FeS}_{(n+1)}$ with impurities such as Cu, Ni and Co.

System. Hexagonal.

Habit. Tabular (basal), prismatic with pyramidal terminations. Sometimes twinned on (1011).

Structure. Massive, less commonly crystalline.

Cleavage. Fair \parallel (0001), poor \parallel (1120),

Fracture. Uneven, brittle.

Hardness. 3.5-4.5.

Spec. Grav. 4.53-4.77.

Lustre. Metallic.

Colour. Bronze-yellow, reddish-yellow, blackish-brown. Cream in vertical reflected light.

Mag. Prop. Strongly magnetic (variable).

Elect. Prop. Good conductor.

Opt. Prop. Opaque. Rotates plane of polarized reflected light.

Characters in Sediments. This species, when present in detrital sediments is invariably irregular (ragged) in form and exhibits characteristic lustre in reflected light (as above). Rapidly alters to limonite, evinced by appearance of ochreous patches noted in many examples.

Occurrence. In the Meadsfoot Beds, Devonian, Torquay, Devon¹; in the Upper Lias—Lower Inferior Oolite sands of the West of England²; in the Arctic Bed (Late Glacial) of the Lea Valley³; in the dune sands of South Wales (derived from the Pennant Grit and Llynfi rock, Swansea Bay)⁴.

Possible Source of Derivation. Basic igneous rocks; metalliferous veins. In some cases authigenic.

REMARKS.—Relatively uncommon in detrital sediments, but when present it is apparent from the preliminary examination of the sample. It is readily dissolved in HCl and therefore does not appear in the cleaned 'heavy' residue. Its magnetic properties, lustre, colour and lower specific gravity serve to distinguish it from pyrite, with which it may possibly be confused.

References

¹ W. E. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 137.

² P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 258.

³ G. M. Davies, *Quart. Journ. Geol. Soc.*, **78**, 1912, p. 247.

⁴ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 323

QUARTZ

[Vol. I, Pl. 8c, facing p. 224 and Pl. 34 A E, between pp. 160 161]

Chem. Comp. SiO₂.

System. Trigonal.

Habit. Prismatic, with rhombohedral terminations, (10 $\bar{1}$ 1) and (0 $\bar{1}$ 11).

Sometimes twinned about c or on (11 $\bar{2}$ 2).

Structure. Crystalline, cryptocrystalline, massive.

Cleavage. Rare \parallel (10 $\bar{1}$ 1) and (0 $\bar{1}$ 11).

Fracture. Conchoidal.

Hardness. 7.

Spec. Grav. 2.66.

Lustre. Vitreous.

Colour. Colourless, purple, black, pink, yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\epsilon \approx 1.553$, $\omega \approx 1.544$. Birefringence weak, $\epsilon - \omega = 0.009$. Optically uniaxial, positive. Rarely biaxial with $2E = 12^\circ - 24^\circ$ (*A. N. Winchell*). Prismatic sections give straight extinction. Slow vibrations \parallel length of crystal (ϵ).

Characters in Sediments. Variable in form and size, but usually in sub-angular, irregularly-shaped grains unless occurring in aeolian deposits, when roundness is marked. Very beautiful, doubly terminated euhedra occur in some sediments, often evidence of secondary crystallization (external crystal faces in optical continuity with central nucleus). The common character of detrital quartz is that of the shapeless, slightly turbid grain with sharply defined inclusions: diagnosed by its low R.I. (almost the same as Canada balsam) and, in the majority of cases, by the 'concentric ring' interference colours yielded by other than basal grains, the latter are isotropic and normally exhibit a positive interference figure. Inclusions are either fluid or mineral; the latter may be rutile, apatite, sillimanite, tourmaline, zircon or iron-ores, the former being gaseous or liquid, carbon dioxide, water, etc. Grains often exhibit undulose extinction due to strain.

Occurrence. Ubiquitous in detrital sediments. The following examples have been selected as covering practically all variations:—in the Torridonian Sandstone of Scotland¹; in the Malvern Quartzite (Cambrian)²; in the Old Red Sandstone of the Cardiff district³; in the Carboniferous Limestone of Halkyn, N. Wales⁴; in the Millstone Grit of Yorkshire⁵; in the Keuper Marls of Charnwood, Leicestershire⁶; in the Penrith Sandstone (Permian) of Penrith, Cumberland⁷; in the Wealden Sands of Kent and Sussex⁸; in the Lower Greensand etc., of Surrey⁹; in the later Tertiary deposits of East England¹⁰; in the dune sands of South Wales¹¹; in Dartmoor detritals¹².

Later Records. In Denbigh Grits, Wenlock Greywackes, Wales¹⁴.

Possible Sources of Derivation. Acid and intermediate rock types, more rarely basic. Sedimentary and crystalline metamorphic rocks. Metaliferous veins.

REMARKS.—Quartz is the most prolific constituent of detrital sediments, especially of the arenaceous and argillaceous types. Its detailed study in the 'lighter' portion of the sediment is of great consequence, particularly when inclusions are present; these are, by their nature and abundance, frequently valuable indices of provenance¹³.

References

- ¹ J. J. H. Teall, *Geology of the N.W. Highlands*, *Mem. Geol. Surv. Scotland*, 1907, p. 284.
- ² G. S. Sweeting, *Proc. Geol. Assoc.*, **38**, 1927, p. 550.
- ³ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 497.
- ⁴ Author's observations (see Pl. 34C).
- ⁵ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 259.
- ⁶ T. O. Bosworth, *Keuper Marls around Charnwood*, *Leicester Lit. and Phil. Soc.*, 1913, p. 89.
- ⁷ Well-known occurrence: see A. Harker, *Petrology for Students* (University Press, Cambridge), 1954, p. 198.
- ⁸ Author's observations, particularly Tunbridge Wells Sand (Wealden) of Eridge, etc., Sussex.
- ⁹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, p. 87.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 335.
- ¹¹ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 323.

¹² A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 46.

¹³ W. Mackie, *Trans. Edinburgh Geol. Soc.*, 7, 1897, p. 148. (Inclusions in quartz, etc.)

¹⁴ W. A. Cummins, *Geol. Mag.*, 94, 1957, p. 440.

General References

P. G. H. Boswell, *British Resources of Sands and Rocks used in Glass-making*, 2nd ed. (Longmans Green, London), 1918 (for British quartzose sands of different stratigraphical ages, size and shape of grains, mechanical analyses, etc.).

C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 416 (for alluvial quartz and varieties).

P. Vigoroux, *Quartz Oscillators and their Applications* (H.M.S.O., London), 1939. Contains considerable information *inter alia* on quartz crystals, their structure and physical properties, with many references.

RIEBECKITE

(AMPHIBOLE GROUP)

Chem. Comp. $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot \text{FeO} \cdot 5\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Prismatic. Often vertically striated || c.

Structure. Crystalline.

Cleavage. Perfect || (110) at 124° .

Fracture. Irregular.

Hardness. 4.

Spec. Grav. 3.44.

Lustre. Vitreous, resinous.

Colour. Dark blue to black. Translucent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Weak conductor.

Opt. Prop. R.I. high, $\alpha = 1.697$, $\beta = 1.700$, $\gamma = 1.703$. Birefringence weak, $\gamma - \alpha = 0.006$. Optically biaxial, negative. Optic axial plane \perp (010). $Bxa = X \wedge c = 0^\circ - 5^\circ$ in β . $Bxo = Z \perp$ (010). $X = b$. Optic axial angle large. Strong dispersion. Pleochroism strong: $X =$ indigo blue, green or green-blue $> Y =$ brown-yellow, violet or yellow $> Z =$ grey, yellow, black. Positive form known (fibrous variety *crocidolite*) in which $Z = b$, $Y \wedge c = 0^\circ \pm$. Also Y may = b when $X \wedge c = 1^\circ - 8^\circ$.

Characters in Sediments. Riebeckite is a rare detrital mineral and often difficult to confirm optically owing to its deep colour. As in igneous rocks, it tends to occur (in sediments) in shapeless, ragged grains. Sometimes striations can be discerned which, together with colour, high R.I. and pleochroism, aid diagnosis. Differs from glaucophane (p. 113) in depth of colour and negative elongation.

Occurrence. In oil borings in Egypt¹; in the Plateau Gravel, Sevenoaks, Kent²; in the sands of Tuscany, Italy³; in shore sand, S. coast Greenland (*crocidolite*)⁴.

Possible Sources of Derivation. Soda-bearing igneous rocks (acid and intermediate types); metamorphic rocks.

References

- ¹ T. W. Bowman, Report on Boring for Oil in Egypt, *Section III, Eastern Desert and Adjoining Islands. Mines and Quarries Dept.*, Egypt, 1931.
² F. Chapman, *Geol. Mag.*, 1900, p. 404.
³ I. Chelussi, *Boll. Soc. geol. ital.*, 29, 1910, p. 207.
⁴ R. D. Crommelin, *Meddelelser om Grønland*, 113, 1937.

ROMIETE

(LEWISITE)

[Pl. 35, between pp. 160-161]

Chem. Comp. [(Ca, Fe, Mn, Na)₂(SbTi)₂O₆(O, OH, F)].*System.* Isometric; hexoctahedral.*Habit.* Octahedral. Occasional twinning on (111).*Structure.* Crystalline.*Cleavage.* Imperfect || (111).*Fracture.* Irregular.*Hardness.* 5.5-6.5.*Spec. Grav.* 4.7-5.4.*Lustre.* Vitreous.*Colour.* Yellow, yellowish-brown. Transparent to translucent.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. very high, $n = 1.81-1.87$, 2.09 in ferroan romeite. Isotropic or strongly birefringent in some varieties (0.026).*Characters in Sediments.* Characteristic rounded, yellowish-brown octahedral grains with black borders due to high R.I. (seen under microscope).*Occurrence.* In eluvial sands, Tripuhy, Minas Geraes, Brazil¹.*Possible Sources of Derivation.* Mineral veins.

REMARKS.— A very rare but beautiful detrital species.

Reference

- ¹ E. Hussak and G. T. Prior, *Miner. Mag.*, 11, 1895, p. 80.

General Reference

- J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, p. 1022.

RUBY

(VARIETY OF CORUNDUM, *q.v.* p. 89)

RUTILE

[Pl. 36A, B, between pp. 160-161]

Chem. Comp. TiO₂.*System.* Tetragonal.*Habit.* Prismatic; acicular. Frequently striated || principal axis c, with transverse striae || (101) due to polysynthetic twinning. Sometimes twinned about (101) either geniculate or as a network (sagenite).

Structure. Crystalline.

Cleavage. Good \parallel (110) and (100). Occasionally \parallel (111).

Fracture. Subconchoidal.

Hardness. 6-6.5.

Spec. Grav. 4.18-4.25.

Lustre. Metallic, adamantine, vitreous.

Colour. Red, reddish-brown, yellow.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\epsilon = 2.903$, $\omega = 2.616$. Birefringence extreme, $\epsilon - \omega = 0.287$. Optically uniaxial, positive. Straight extinction. Interference figure anomalous in twinned crystals, giving biaxial characters, 'twinning bands crossing basal sections of the uniaxial mineral; in these bands the optic plane is \parallel (110)' (*A. N. Winchell*). Length slow. Red and brown varieties usually pleochroic, weak: reddish-brown to brown or yellow. Maximum absorption direction \parallel principal axis.

Characters in Sediments. Two contrasted types of rutile are met with in sediments: well-formed prismatic grains with pyramidal terminations, often slightly rounded and anhedral fractured grains; the former are usually 'foxy-red' or reddish-brown in colour, the latter being commonly of an amber tint. The degree of rounding of grains is a variable factor, often being slight compared with associated minerals. Long, slender 'needles' of a red-brown to almost black colour are highly characteristic of many metamorphosed, argillaceous rocks, *e.g.* phyllites, slates, etc. In addition, geniculate twins are found in certain sands, especially in alluvials, the two individuals making an angle of about 65° with one another. Many prismatic grains exhibit characteristic striations running obliquely to the prism edge, due to polysynthetic twinning \parallel (101). Inclusions of iron-ore rare. Diagnosed chiefly by tetragonal (prismatic) form and cleavage, brilliant metallic to vitreous lustre, colour, high R.I. and diagonal striae when developed.

Occurrence. Extremely common in detrital sediments from all geological horizons. The following occurrences and records cover practically all types noted:—in the Bunter Pebble Beds of the West of England¹; in the Upper Lias—Lower Inferior Oolite sands of the West of England²; in the Northampton Ironstone³; in the Upper Tunbridge Wells Sands (Wealden), Tunbridge Wells, Kent⁴; in the Lower Greensand of N.W. Wiltshire⁵ and Cambridgeshire⁶ etc.; in all Lower Tertiary sands of the Hampshire and London basins⁷; in the Pliocene sands of Cornwall⁸; in the later Tertiary deposits of East England⁹; in the dune sands of South Wales¹⁰; in Dartmoor detritals¹¹.

Later Records. In Lower Greensand, E. Kent¹²; in Lower Greensand, Western Weald¹³.

Possible Sources of Derivation. Acid igneous rocks, crystalline metamorphic rocks. Frequently derived *in situ* from the decomposition of ilmenite.

REMARKS.—Sagenite, the 'lattice' form of rutile, composed of a number of individuals involved in geniculate twinning, is an infrequent occurrence in detrital sediments. When present it probably owes its

preservation to a host such as biotite or a member of the chlorite group from which it is released by their decomposition.

References

- ¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 622.
- ² P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 253.
- ³ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 380.
- ⁴ H. B. Milner, *Proc. Geol. Assoc.*, **34**, 1923, p. 49 and *Pl. 5*.
- ⁵ Author's observations.
- ⁶ R. H. Rastall, *Geol. Mag.*, **56**, 1919, p. 219.
- ⁷ General observations; see particularly P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1915, pp. 576, 581 and table iv (for N.E. London basin); S. W. Wooldridge, *Proc. Geol. Assoc.*, **35**, 1924, p. 379 (for Bagshot Beds of Essex).
- ⁸ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, pp. 359, 361.
- ⁹ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 338.
- ¹⁰ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 322.
- ¹¹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 34; also A. Brammall and H. F. Harwood, *Miner. Mag.*, **22**, 1923, p. 20.
- ¹² G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- ¹³ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

General References

- C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 422 (for alluvial rutile, sagenite, etc.).
- P. G. H. Boswell, Some Rare Detrital Minerals in British Sedimentary Rocks, *Trans. Geol. Soc. Glasgow*, **18**, 1927, p. 129.
- A. B. Dick, On Needles of Rutile in the Test of *Bathysiphon argenteus*, *Trans. Edinburgh Geol. Soc.*, **12**, 1928, p. 19.
- R. H. Rastall, On Rutile in the Dogger, *Geol. Mag.*, **76**, 1939, p. 109.

SANADINE

(VARIETY OF ORTHORCLASE FELSPAR, *q.v.* p. 155)

SAPPHIRE

(VARIETY OF CORUNDUM, *q.v.* p. 89).

SCHEELITE

Chem. Comp. CaWO_4 .

System. Tetragonal; dipyramidal.

Habit. Octahedral (011) or (112); tabular (001); twinned on (110).

Structure. Crystalline.

Cleavage. Good \parallel (101), less common \parallel (112).

Fracture. Uneven.

Hardness. 4.5–5.

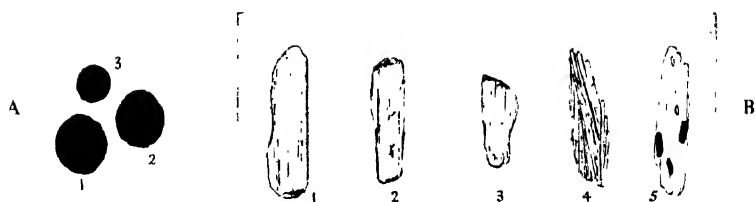
Spec. Grav. 6.1.

Lustre. Vitreous to adamantine.

Colour. Colourless, white, yellow, brown.

Mag. Prop. Weakly magnetic.

Elect. Prop. Poor conductor.

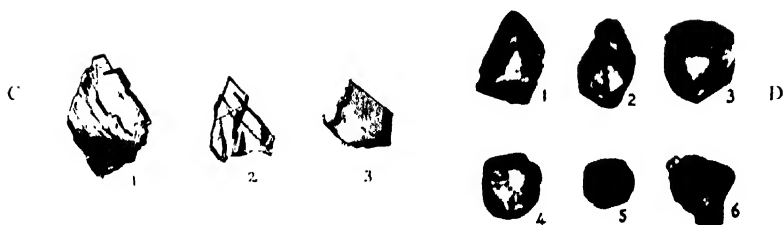


A. SPHERULITIC SIDERITE.

A 1 3. Fairlight Clay, Fairlight Glen, Hastings, Sussex [x 45]

B. SILLIMAITE.

B 1 4. Pliocene Sand, Bentley, Suffolk [1 3, x 45] [4, x 60]
 B 5. Recent Sand, Dinard, Brittany [x 45]



SPHAERULITE

C 1 3. Middle Lias Ironstone, Cleveland, Yorkshire [x 40]

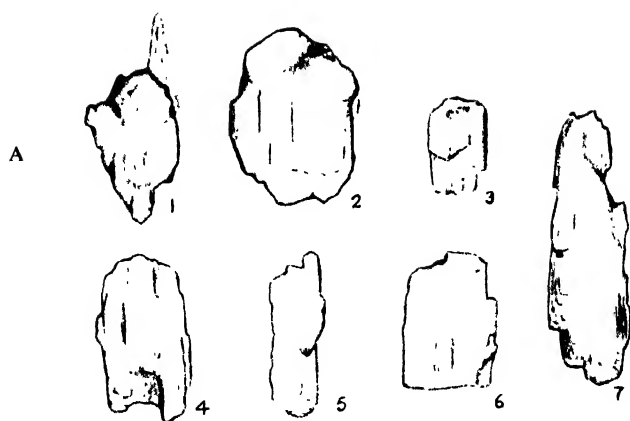
D 1 3. Dogger Ironstone, Mid Jurassic, Yorkshire [x 116]

D 4 6. Fuller's Earth (Aptian), Surrey [x 83]



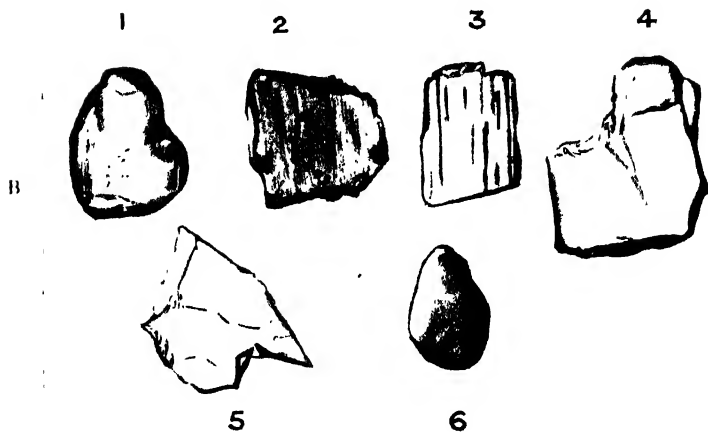
E. SPINEL.

Alluvials Ceylon [x 59]



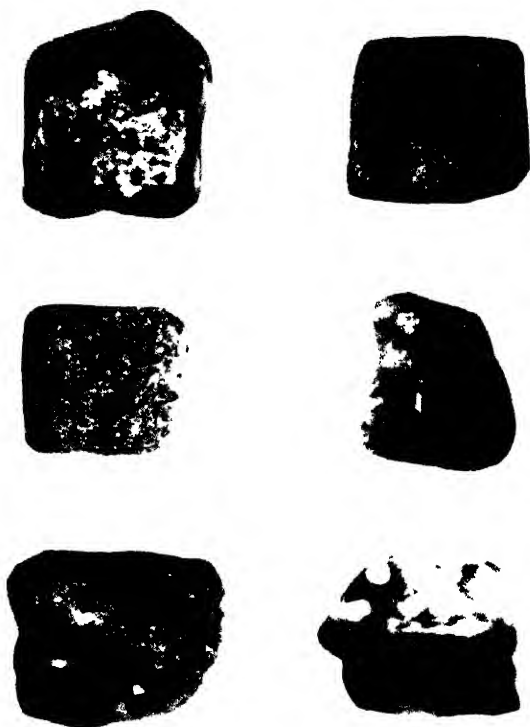
A. SPODUMENE.

- A 1 6 Recent Sand, Carrickmines, Ireland [x 60]
 A 7 Annamoe River, Ireland [x 80]
 (From brush-drawings by J. Smithson.)



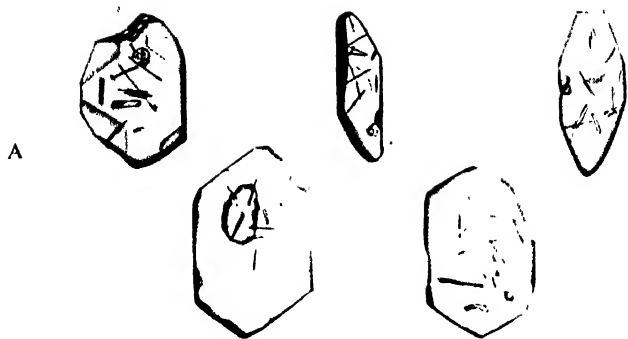
B, C. STAUROLITE.

- B 1 Pliocene Sands, St. Erth, Cornwall [x 70]
 B 2 Lower Greensand, N.W. Wiltshire [x 70]
 B 3 5 Alluvials, W. Africa [x 70]
 B 6 Blown Sand, Newgate, Pembrokeshire [x 70]
 C. Lower Greensand, Isle of Wight [x 59]



THORIANTHITE.

Gem Gravels, Balagoda District, Sabaragamuwa Province, Ceylon
 [Top & trans. light, x 25.]



A, B TITANITE

A Fuller's Earth, Nuthfield [x 200] (From brush-drawings by E. F. Newton)

B Shore Sand, Galway [x 57]



C TOPAZ

C 1, 2 Alluvials, Nigeria [x 45]

C 3 Lower Greensand, Poulshott Green, N.W. Wilts. [x 45]

C 4 Pliocene Sand, St. Keverne, Cornwall [x 45]

Opt. Prop. R.I. high, $\epsilon = 1.935$, $\omega = 1.919$. Birefringence moderate, $\epsilon - \omega = 0.016$. Optically uniaxial, positive. Straight extinction. Non-pleochroic.

Characters in Sediments. As subangular octahedral grains, less commonly tabular. Sometimes striated.

Occurrence. In monazite-bearing sands, Yellowknife geologic province, North West Territories, Canada¹; in bed-rock sands, Brandy Gill and Grainsgill Beck, Carrock Fell, Cumberland².

Possible Sources of Derivation. Crystalline igneous rocks; pegmatites; contact-altered limestones; mineral veins.

REMARKS.—Strongly fluorescent in ultra-violet light (see Vol. I, Ch. XII, p. 455).

References

¹ R. E. Folinsbee, *Trans. Roy. Soc. Canada*, **49**, Ser. III, 1955, p. 7.

² Author's observations.

SELENITE

(See GYPSUM, p 118.)

SERPENTINE

Hitherto the record of 'serpentine' in sediments has implied either fragmentary serpentine rock or the minerals 'antigorite' (p. 46) or 'chrysotile' (p. 83). Antigorite is now classed as an end-member of the chlorite group (p. 78), wherein it undoubtedly possesses close affinities with other species so designated. Chrysotile is a distinctive species, but apparently dimorphous with antigorite; it is therefore treated separately in this book and the term 'serpentine' as a mineral is dropped. References to occurrences of 'serpentine' are, however, given here for convenience:—

In the Devonian and Culm sediments of the Torquay district¹; in the Permian Rocks of the Torquay promontory²; in the new Red Sandstone of the West of England³; in the sands of the Upper Lias-Lower Inferior Oolite of the West of England⁴; in the shore sands in proximity to the serpentine masses of the Lizard district, Cornwall⁵; in recent deposits of Pavia etc., Northern Italy⁶; in deposits of doubtful age (? Eocene) of Marazion, Cornwall⁷.

References

¹ W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, pp. 139, 142.

² W. G. Shannon, *Proc. Geol. Assoc.*, **38**, 1927, p. 134.

³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 239.

⁴ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 252.

⁵ Author's observations.

⁶ E. Tacconi, *Rend. R. Ist. lombardo*, ser. 2, **34**, 1901, p. 873.

⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, pp. 213, 226.

SIDERITE (CHALYBITE)

[Pl. 37A, between pp. 176–177]

Chem. Comp. FeCO_3 .

System. Trigonal.

Habit. Simple rhombohedron, often with curved faces. Spherulitic.

Structure. Crystalline, massive, compact, radiating in spherulites.

Cleavage. Perfect rhombohedral \parallel (10 $\bar{1}$ 1).

Fracture. Uneven. Brittle.

Hardness. 3.5-4.

Spec. Grav. 3.78-3.89.

Lustre. Vitreous, dull.

Colour. Shades of brown or grey. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\omega = 1.875$, $\epsilon = 1.633$. Birefringence extreme, $\omega - \epsilon = 0.242$. Optically uniaxial, negative. In translucent grains, 'twinkling', due to different R.I. values, noted on rotation of polarizer alone. Radiating masses exhibit brush-polarization (or 'black cross') effects. Often possesses distinct absorption.

Characters in Sediments. Subangular or rounded rhombohedral grains determined principally by cleavage. Also as spherulitic or slightly ellipsoidal grains of characteristic form, colour and traces of radiate structure on fractured edges. Diagnosed chiefly by form, yellow-brown colour, both R.I. values *higher* than Canada balsam (unlike calcite (p. 67), dolomite (p. 97), magnesite (p. 139) and absorption).

Occurrence. In the Devonian rocks of the Torquay district¹; in the Millstone Grit, Snail Green, near Bradford²; in the Upper Coal Measures of South Wales³; in the Etruria Marls and Blackband Group (Upper Coal Measures) of Staffordshire⁴; in the Coal Measure Sediments of Durham⁵; in the Marlstone Ironstone (Middle Lias) of Leicestershire⁶; in the Fairlight Clays (Wealden) of Fairlight, Sussex⁷; in St. Ives Bay sand, Cornwall⁸.

Later Records. In Liassic Ironstones, Cleveland, Yorkshire⁹; in Northampton Sand Ironstone Field¹⁰, in Beach Sand, Carbis Bay, Cornwall¹¹.

Possible Sources of Derivation. Clay ironstone and allied stratified deposits, also from metalliferous veins.

REMARKS. - By no means a common mineral in detrital sediments, only occurring locally under suitable conditions. Siderite is insoluble in cold dilute HCl (unlike calcite (p. 67) and dolomite (p. 97)).

References

- ¹ W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 142.
- ² J. A. Butterfield, *Trans. Leeds Geol. Assoc.*, **5**, 1933, p. 97.
- ^{3,4} F. Spencer, *Quart. Journ. Geol. Soc.*, **81**, 1925, p. 675.
- ⁵ J. G. Kellett, *Proc. Univ. Durham Phil. Soc.*, **7**, 1926, p. 208.
- ⁶ W. A. Richardson, *Trans. Inst. Min. Eng.*, **60**, 1921, p. 337.
- ⁷ H. B. Miner, *Proc. Geol. Assoc.*, **36**, 1925, p. 315; also E. Spencer, *loc. cit. sup.*, p. 670.
- ⁸ T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 122.
- ⁹ T. H. Whitehead and ors., *Mem. Geol. Surv.*, 1952, p. 17.
- ¹⁰ J. H. Taylor, *Mem. Geol. Surv.*, 1949, p. 2.
- ¹¹ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General Reference

E. Spencer, *On Occurrences of Spherulitic Siderite, etc., in Sediments*, loc. cit., p. 232.

SILLIMANITE

[Pl. 37B, between pp. 176-177]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$.

System. Orthorhombic.

Habit. Prismatic, rectangular, with irregular terminations, fibrous.

Sometimes vertically striated $\parallel c$.

Structure. Crystalline.

Cleavage. Good $\parallel (010)$.

Fracture. Irregular.

Hardness. 6-7.5.

Spec. Grav. 3.23-3.25.

Lustre. Vitreous.

Colour. Usually colourless, yellow, pale shades of brown, green or grey. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.659$, $\beta = 1.660$, $\gamma = 1.680$. Birefringence moderate, $\gamma - \alpha = 0.021$. Optically biaxial, positive. Optic axial plane $\parallel (010)$. Straight extinction \parallel prism edge. $Bxa = Z \perp (001)$, i.e. $\parallel c$, $Z = c$. $X = b$. $2V = 20^\circ$, $2E = 33^\circ$. Occasionally pleochroic, especially if much coloured: $X =$ pale brown or yellow, $Y =$ brown or green, $Z =$ dark brown or blue. Strong dispersion, $\rho > \nu$.

Characters in Sediments. Usually found as slender prisms or fibres, sometimes flattened, with fractured or irregular terminations. Tendency to display traces of longitudinal 'splitting'. Flattened grains $\parallel (001)$ exhibit good biaxial figure and low birefringence due to $\beta - \alpha = 0.001$. Grains with regular striations are comparatively rare; curved forms are occasionally met with. Inclusions of spinel, biotite or glass (*A. N. Winchell*).

Occurrence. In the Bunter Pebble Beds of the West of England¹; in the New Red Sandstone of the West of England²; in the Lower Greensand of Limpsfield, Surrey³; in the Lenham Beds, Sanderstead, Surrey⁴; in the Red Crag, Bentley, Suffolk⁵; in the Northampton Ironstone⁶; in the Lower Greensand of the Dorking-Leith Hill district, Surrey⁷; in the Lower Eocene deposits of the North-Eastern part of the London Basin⁸; in the later Tertiary deposits (Red Crag, Norwich Crag, Chillesford Beds, Forest Bed and *Leda myalis* Bed) of East England⁹; in deposits of doubtful age, Marazion, Cornwall¹⁰; in the Dartmoor detritals¹¹. 'Its occurrences in the Bunter, Upper Lias, Inferior Oolite, Callovian, Thanet Beds, Reading Beds, Claygate Beds, Bagshot Beds, Upper Headon Beds, and the Pliocene of East Anglia and Cornwall, as well as more recent deposits in Scotland, Ireland and England, are sporadic and rare¹²'.

Later Records. In Lower Greensand, E. Kent¹³; in Lower Greensand, Western Weald¹⁴.

Possible Sources of Derivation. Crystalline metamorphic rocks.

REMARKS.—Sillimanite is essentially a local species in Britain. It is distinguished from topaz and andalusite by its higher birefringence and smaller axial angle, andalusite having negative, sillimanite positive elongation; from kyanite, which at first sight it often resembles, by straight extinction, high interference colours and lower R.I.

References

- ¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 621.
- ² H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 231.
- ³ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, p. 91.
- ⁴ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, **37**, 1926, p. 99.
- ⁵ Author's observations.
- ⁶ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 375.
- ⁷ H. A. Hayward, *Proc. Geol. Assoc.*, **43**, 1932, p. 1.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **72**, 1916, p. 536.
- ⁹ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 340.
- ¹⁰ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ¹¹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 47.
- ¹² P. G. H. Boswell, *The Rarer Detrital Minerals of British Sedimentary Rocks*, *Trans. Geol. Soc. Glasgow*, **18**, 1926–27, p. 140.
- ¹³ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- ¹⁴ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

SODALITE

Chem. Comp. $2[\text{Na}_4\text{Al}_3\text{Si}_3\text{O}_{12}\text{Cl}]$.

System. Isometric.

Habit. Dodecahedral, granular.

Structure. Crystalline, occasionally twinned.

Cleavage. Poor || (110).

Fracture. Irregular.

Hardness. 5·5–6.

Spec. Grav. 2·14–2·4.

Lustre. Dull.

Colour. Colourless, pale blue, yellow, grey.

Mag. Prop. Non-magnetic.

Elect. Prop. —

Opt. Prop. R.I. low, 1·480–1·510. Optically isotropic or rarely birefringent around inclusions.

Characters in Sediments. Irregularly shaped, colourless or blue-grey grains.

Occurrence. In recent deposits, shore sands, S. Coast, Greenland¹.

Possible Sources of Derivation. Alkaline igneous rocks; an alteration product of nepheline.

REMARKS.—A very rare detrital mineral, often associated with nepheline (p. 150) and only to be anticipated where appropriate parent-rocks are locally under contribution. Rapidly alters to zeolites, carbonates, etc.

References

- ¹ R. D. Crommelin, *Meddelelser om Grønland*, **113**, 1937.

SPESSARTITE

(GARNET GROUP)

Chem. Comp. $3(\text{Mn, Fe, Ca})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$.*System.* Isometric.*Habit.* Dodecahedral, trapezohedral.*Structure.* Crystalline, granular.*Cleavage.* None.*Fracture.* Uneven.*Hardness.* 7.*Spec. Grav.* 3.8–4.25.*Lustre.* Vitreous.*Colour.* Salmon pink, yellow, brown, transparent to translucent.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Poor conductor.*Opt. Prop.* R.I. very high, $n = 1.805$. Optically isotropic. Some specimens show distinct anisotropism, probably due to strain.*Characters in Sediments.* Spessartite is a rare detrital mineral but is to be identified by its colour, very high R.I. and tendency to show superficial alteration to biotite.*Possible Sources of Derivation.* Acid igneous rocks, e.g. granite, rhyolite; also low-grade metamorphosed sediments.

SPHALERITE (ZINC BLENDE)

[Pl. 37C, D, *between pp.* 176–177]*Chem. Comp.* ZnS. Sometimes with Fe.*System.* Isometric.*Habit.* Tetrahedral, dodecahedral or combination of cube and dodecahedron. Frequently twinned: twin lamellae || tetrahedron faces.*Structure.* Crystalline, massive, granular.*Cleavage.* Perfect || (110).*Fracture.* Conchoidal.*Hardness.* 3.5–4.*Spec. Grav.* 4–4.1.*Lustre.* Adamantine, metallic, resinous. Grey in vertical reflected light.*Colour.* Black, brown, yellow; sometimes green. Opaque, sometimes translucent.*Mag. Prop.* Weakly magnetic to moderately magnetic when Fe is present.*Elect. Prop.* Good conductor.*Opt. Prop.* R.I. very high (in translucent crystals), $n = 2.37$. Increases with Fe content. Isotropic. Sometimes anisotropic due to strain.*Characters in Sediments.* This mineral may either occur in quite opaque tetrahedral or dodecahedral grains or in translucent brown granules of high refractive index and obvious isotropism. If in the

opaque form, the striations || the tetrahedral faces are usually developed and are very characteristic. Its resinous lustre and indication of a perfect dodecahedral cleavage are further properties to be looked for. In some sediments, *e.g.* clays, sphalerite occurs in significant spherical shapes with or without radiating structure suggestive of replacement of organic bodies. The translucent coloured grains (colouring may be zonal) are extremely difficult to differentiate from other similarly coloured detrital minerals and chemical tests on bulk material (if possible) are desirable. Distinguished from rutile, brookite, cassiterite and titanite by the anisotropism of those species; but may be confused with brown garnet, chromite or picotite if in small grains.

Occurrence. In the Middle Lias (Cleveland Ironstone) of Yorkshire¹; in the Jurassic Fuller's earth of Combe Hay, Bath, Somerset²; in the Fuller's earth (Aptian) of Redhill, Surrey³; also at Nutfield, Surrey⁴; in the shore sand of Lelant, Cornwall⁵.

Later Records. In Fuller's earth, Western Weald⁶.

Possible Sources of Derivation. From veins and irregular ore bodies in limestones; from metalliferous veins associated with galena, pyrite, copper ores, etc. In Fuller's earth, clays, etc., may be formed as a result of organic decomposition.

REMARKS.—In a personal communication to the author, G. M. Davies draws attention to the commonly noted association of sphalerite and Fuller's earth, not only in Aptian deposits, but also in the Jurassic Fuller's earth, *e.g.* Combe Hay, near Bath.

References

- ¹ J. E. Stead, *Proc. Cleveland Inst. Eng.*, 1910, p. 75; also A. F. Hallimond, *Iron Ores, Mem. Geol. Sur., Min. Res. Gt. Brit.*, 29, 1925, p. 52, also F. Smithson, *Proc. York. Geol. Soc.*, 22, 1933, p. 153.
- ² E. F. Newton, *Proc. Geol. Assoc.*, 48, 1937, p. 188.
- ³ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, p. 86.
- ⁴ E. F. Newton, *loc. cit.*, p. 179.
- ⁵ Author's observation.
- ⁶ G. V. Wood, *Proc. Geol. Assoc.*, 67, 1956, p. 127.

General Reference

H. H. Thomas and D. A. MacAlister, *The Geology of Ore Deposits* (Arnold London), 1909.

SPHENE

(See TITANITE, p. 191)

:

SPINEL

(SPINEL GROUP)

[Pl. 37E, between pp. 176-177]

Chem. Comp. MgO . Al₂O₃.

System. Isometric.

Habit. Octahedral.

Structure. Crystalline.

Cleavage. Poor || (111).

Fracture. Conchoidal.

Hardness. 8.

Spec. Grav. 3.6.

Lustre. Vitreous.

Colour. Shades of red, reddish-yellow, blue, green.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $n = 1.718$.

Characters in Sediments. Generally occurs as well rounded octahedral grains, much 'pitted' from uneven abrasion. The conchoidal fracture, if developed, is very characteristic. Recognized by its high R.I., colour and isotropism.

Occurrence. In Keuper rocks at Wimslow, Cheshire¹; in the Upper Kimmeridge Clay and Portland Sand of Dorset, Wiltshire, Oxfordshire and Buckinghamshire²; in the Jurassic 'Sands' from the North Cotteswolds³; in the Carstone and Red Chalk of Yorkshire and Lincolnshire⁴; in the Ashdown Sand of Etchingham and Robertsbridge, Sussex⁵; in the Folkestone Beds of the Dorking-Leith Hill district, Surrey⁶; in the Lenham Beds, Sanderstead, Surrey⁷; in the Thanet Beds of Suffolk and Essex⁸; in the dune sands of South Wales⁹; in the Dartmoor detritals¹⁰; in St. Ives Bay sand, Cornwall¹¹; in beach sands between St. John's river and St. Augustine, Florida, U.S.A.¹²; beach sands between Charleston, South Carolina and Miami, Florida, U.S.A.¹³.

Possible Sources of Derivation. Metamorphosed limestone, crystalline schist, dolomitic limestone.

REMARKS.—Common red spinel seems to be extremely rare in detrital sediments, though its resemblance to almandine garnet may have caused it to be overlooked in some instances. It differs from garnet in its lower S.G., non-magnetic properties and usual octahedral habit, but positive diagnosis by the microscope alone is certainly difficult. Appeal to R.I. test by immersion in methylene iodide is suggestive: spinel is nearly always less than, garnet greater than, that liquid (1.737) [*A. Brammall*]. Other members of the spinel group recorded from sediments are described, ceylonite (p. 72), chromite (p. 81), hercynite (p. 121), magnetite (p. 140), picotite (p. 161).

References

¹ S. W. Alty, *Proc. Liverpool Geol. Soc.*, **14**, 1926, p. 278.

² E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 240.

³ J. G. A. Skerl, *Proc. Cotteswold Nat. Field Club*, **23**, 1925, p. 153.

⁴ H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, **20**, 1926, p. 349.

⁵ A. A. Fitch, *Proc. Geol. Assoc.*, **41**, 1930, p. 53.

⁶ H. A. Hayward, *Proc. Geol. Assoc.*, **43**, 1932, p. 1.

⁷ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, **37**, 1926, p. 92.

⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **71**, 1916, p. 536.

⁹ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 321.

¹⁰ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 47.

¹¹ T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 122.

¹² J. H. C. Martens, 19th Ann. Rep. Florida State Geol. Surv., 1928, p. 130.

¹³ J. H. C. Martens, *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1580.

SPODUMENE (TRIPHANE)

(PYROXENE GROUP)

[Pl. 38A, between pp. 176-177]

Chem. Comp. $\text{Li}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$.

System. Monoclinic.

Habit. Prismatic, often flattened \parallel (100). Also twinned about (100). Frequently exhibits vertical striae.

Structure. Crystalline, massive, cleavable. Lamellar \parallel (100) due to twinning.

Cleavage. Perfect \parallel (110), parting \parallel (010), rarely (100).

Fracture. Subconchoidal, irregular.

Hardness. 6.5-7.

Spec. Grav. 3.1-3.2.

Lustre. Vitreous, pearly on (110).

Colour. Green, greenish-white, mauve, yellow, pink. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.660$, $\beta = 1.666$, $\gamma = 1.676$. Birefringence moderate, $\gamma - \alpha = 0.016$. Optically biaxial, positive. Optic axial plane \parallel (010). $Bxa = Z$ inclined at 23° - 27° to c in the obtuse angle β . $Y = b$. Oblique extinction, angle 26° or less. $2V = 54^\circ$ - 60° . Dispersion weak, $\rho < \nu$. Coloured varieties exhibit weak pleochroism: $X = \text{purple} > Y = \text{pink or mauve} > Z = \text{colourless (kunzite) or } X = \text{green} > Y = \text{green} > Z = \text{colourless (hiddenite)}$.

Characters in Sediments. Occurs rarely, either as fairly perfect euhedral crystals not unlike titanite in habit, or in the form of irregular and much fractured prismatic grains of distinctive pale green, greenish-mauve or pink colour; the former approximate the variety hiddenite, the latter (pink to lilac) kunzite. Characterized by prismatic cleavage, often traces of parting \parallel (010), oblique extinction angle up to 26° and sometimes by the presence of a fibrous alteration product (cymatolite). Indeterminate inclusions observed.

Occurrence. In Pliocene-Pleistocene and Recent sands of Southern California¹; in rocks of similar age in the Lazard area, San Joaquin Valley, California²; in sands and soils derived from granite, Carrickmines Golf Course, Dublin district³.

Possible Sources of Derivation. Granite, granite pegmatite, gneiss, mica-schist.

REMARKS.—The records of this mineral occurring in detrital sediments are very scanty and it has probably been overlooked in certain cases of pyroxene-rich sediments where, from the nature of the contributing parent-rocks, it might have been expected to occur. Its optical properties are sufficiently distinctive for diagnosis, coupled with the characteristic

habit, cleavage and colour. It readily yields a red flame with the blow-pipe (Li_2O).

References

- ¹ Author's observations.
- ² R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, **11**, 1927, p. 363.
- ³ F. Smithson, *Geol. Mag.*, **65**, 1928, p. 24 and Fig. 2 (11, 12).

General Reference

- C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 430 (for alluvial spodumene, kunzite, etc.).

STAUROLITE

[Pl. 38B, C, between pp. 176–177]

Chem. Comp. $2\text{FeO} \cdot 5\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Prismatic; sometimes twinned about (032) cruciform, or on (232) giving cross at $60^\circ 31'$.

Structure. Crystalline.

Cleavage. Good \parallel (010), rarely \parallel (110).

Fracture. Subconchoidal, hackly.

Hardness. 7–7.5.

Spec. Grav. 3.65–3.77.

Lustre. Vitreous.

Colour. Reddish-brown, brown, brownish-yellow, straw-yellow. Transparent to translucent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.736$, $\beta = 1.741$, $\gamma = 1.746$. Birefringence moderate, $\gamma - \alpha = 0.010$. Optically biaxial, positive. Optic axial plane \parallel (100). $Bxa = Z \parallel c \perp$ (001). $X \parallel b$, $Y \parallel a$. $2V = 88^\circ \pm$. Prismatic-sections show straight extinction. Pleochroism moderate: $X =$ colourless $< Y =$ pale yellow $< Z =$ golden yellow. Dispersion weak, $\rho > \nu$.

Characters in Sediments. Well crystallized grains are comparatively rare, the usual type being irregular or somewhat platy grains determined largely by cleavage, having marked hackly fracture and haphazard boundaries. In a few cases, very perfect euhedra are seen, generally of a delicate lemon-yellow tint and exhibiting the characteristic pleochroism. Grains with 'concertina' boundaries (due probably to solution) are sometimes met with. Intensity of pleochroism varies greatly. Inclusions are common, especially quartz; garnet, tourmaline, rutile, biotite and carbonaceous matter have all been observed; such inclusions are usually commoner in the deeper coloured varieties. H. H. Thomas has described some well formed crystals from the New Red Sandstone of the West of England, which are tabular \parallel (010), modified by (110) and terminated by forms (101) and (001); such grains constitute a rare type in sediments generally. A still rarer type in detrital sediments is that of the cruciform twin, the two

individuals being disposed at right angles. Superficial decomposition to a member of the chlorite group or to green mica may be noted in some instances.

Occurrence. A widespread mineral in British strata; the following selection indicates the range of this mineral and exemplifies all varieties: Upper Llandovery (Silurian), in the Halesowen Sandstone (Upper Carboniferous), in the Keele Beds (Upper Carboniferous), the Enville and Permian rocks, Bunter and Keuper Sandstones etc., of the English Midlands¹; in the Old Red Sandstone (Downtonian) of the West Midlands²; in the Bunter Pebble Bed of the West of England³; in the Keuper Marls around Charnwood, Leicestershire⁴; in the New Red Sandstone of the West of England⁵; in the Permian Yellow Sands of Yorkshire⁶; in the Upper Lias—Lower Inferior Oolite of the West of England⁷; in the Northampton Ironstone⁸; in the Portland Sand of Dorset⁹; in the Tunbridge Wells Sand (Wealden) of Kent, etc.¹⁰; in the Lower Greensand of Surrey¹¹; in the Carstone of Yorkshire and Lincolnshire¹²; in the Cretaceous and Eocene of Haldon Hills, in the Oligocene of Bovey and Petrockstow, Devonshire¹³; in the Bagshot Beds (Eocene) of Essex¹⁴; in the Pliocene of West Cornwall¹⁵; in the later Tertiary deposits of East England¹⁶; in surface deposits of S.E. Devonshire¹⁷.

Later Records. Lower Greensand, Western Weald¹⁸; Reading Beds, Reading¹⁹; Trinidad Lake Asphalt, Trinidad, B.W.I. (mineral matter)²⁰.

Possible Sources of Derivation. Crystalline schists, contact metamorphic rocks.

REMARKS.—Staurolite often occurs in association with garnet, kyanite and sillimanite in metamorphic rocks, this association being common in many sediments thence derived. Very beautiful alluvial staurolite comes from the Gold Coast, Nigeria etc. (West Africa). See *General Reference* below.

References

- ¹ W. F. Fleet, *Geol. Mag.*, **62**, 1925, p. 98.
- ² W. F. Fleet, *Geol. Mag.*, **63**, 1926, p. 513.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 625 and *Pl.* 32, *Fig.* 7.
- ⁴ T. O. Bosworth, *Quart. Journ. Geol. Soc.*, **68**, 1912, p. 289.
- ⁵ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 234, and *Pl.* 12, *Figs.* 4a, 4b, 4c.
- ⁶ H. C. Versey, *Proc. Yorks. Geol. Soc.*, **20**, 1925, p. 207.
- ⁷ P. G. H. Boswell, *Geol. Mag.*, **61**, 1924, p. 254.
- ⁸ J. G. A. Skerl, *Proc. Geol. Assoc.*, **38**, 1927, p. 382.
- ⁹ M. P. Lutter, *Proc. Geol. Assoc.*, **37**, 1926, p. 83.
- ¹⁰ H. B. Milner, *Proc. Geol. Assoc.*, **34**, 1923, p. 49.
- ¹¹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915–16, pp. 84, 92.
- ¹² H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, **20**, 1926, p. 353.
- ¹³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.
- ¹⁴ S. W. Wooldridge, *Proc. Geol. Assoc.*, **35**, 1924, p. 377.
- ¹⁵ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 358.
- ¹⁶ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 340.

¹⁷ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 147.

¹⁸ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.

¹⁹ P. S. Walder, *Proc. Geol. Assoc.*, **51**, 1940, p. 215.

²⁰ Author's observations.

General Reference

C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 432.

STEATITE (TALC)

Chem. Comp. $3\text{MgO} \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic ? (Pseudo-hexagonal).

Habit. (001) laminae in masses.

Structure. Crystalline, massive, foliated.

Cleavage. Perfect \parallel (001).

Fracture. Difficult.

Hardness. 1.

Spec. Grav. 2.7–2.8.

Lustre. Pearly, resinous.

Colour. White, cream, green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.539$, $\beta = 1.589$, $\gamma = 1.589$. Birefringence strong, $\gamma - \alpha = 0.050$. Optically biaxial, negative. Optic axial plane \parallel (100). $Bxa \rightarrow X = c$ nearly \perp (001). $2V = 6^\circ - 30^\circ$. $2E = 9^\circ - 48^\circ$. (Optic axial angle often nearly zero due to compound laminae.) Dispersion weak, $p > v$.

Characters in Sediments. Grains of steatite are identified by their colour, micaceous habit, usual semi-transparency, low R.I. and strong birefringence. Often exhibits very small optic axial angle due to superimposition of laminae, hence distinction from muscovite. Difficult to diagnose microscopically *per se* unless anticipated from associated minerals or known provenance of sediment.

Occurrence. In the Lower Cambrian, Massif de Ste. Croix, Central Poland¹; in sediments of Cretaceous to Miocene age, Cypress Hills, Saskatchewan, Canada²; in sands (Miocene) of Turin, Italy³; in sands of Bahia, Brazil⁴.

Possible Sources of Derivation. Schist, serpentine. Occasional alteration product of olivine, rhombic pyroxene, etc., in basic igneous rocks.

References

¹ P. Radziszewski, *Bull. Serv. géol. Pologne*, **4**, 1928, p. 500.

² F. J. Fraser, *Summ. Rep. Geol. Surv., Canada*, 1928, p. 44B.

³ L. Colomba, *Atti R. Acad. Sci. Torino*, **31**, 1896, p. 993.

⁴ A. Damour, *Bull. Soc. géol. France*, **13**, 1856, p. 542.

STILPNOMELANE

Chem. Comp. $\text{K}(\text{Fe}'', \text{Fe}''', \text{Al})_{10}\text{Si}_{12}\text{O}_{30}(\text{O}, \text{OH})_{12}$. (M. H. Hey, see under *Remarks* and *Gen. Ref.**)

System. ? Monoclinic.

Habit. Pseudohexagonal.

Structure. Lamellar, foliated, radiated, fibrous.

Cleavage. Perfect \parallel (001).

Fracture. Irregular.

Hardness. $1.5 \pm$.

Spec. Grav. $2.7-3.0$.

Lustre. Pearly, vitreous; sometimes 'brass-like'.

Colour. Brown, green, black.

Mag. Prop. Moderately magnetic.

Elect. Prop. —

Opt. Prop. R.I. high, $\alpha = 1.546$, $\beta = 1.615$, $\gamma = 1.615$. Birefringence strong, $\gamma - \alpha = 0.069$. Optically biaxial, negative. Optic axial angle very small. $X \perp$ (001) $\wedge c$, small. Strongly pleochroic, $X =$ yellow, Y and $Z =$ dark brown or green.

Characters in Sediments. Both in physical and optical characteristics resembles biotite and grains are usually lamellar, determined by cleavage.

Occurrence. In Ashdown Sandstone and Pebble Bed, Wealden Weald, S.E. England¹. (New species to Wealden beds.)

Possible Sources of Derivation. Sedimentary iron-ores or iron-ore veins.

REMARKS.—A mineral of variable composition and uncertain formula (Winchell). M. H. Hey remarks: 'Dana (6th edn.) and others use Stilpnomelane for the ferrous member of the series, and Chalcodite for the ferric, but Hutton (*Min. Mag.* pp. 25–192) has shown that Stilpnomelane from the original locality is a ferric mineral, chemically identical with typical Chalcodite. The name Stilpnomelane has priority over Chalcodite*.

Reference

- ¹ P. Allen, *Quart. Journ. Geol. Soc.*, **104**, 1948, p. 313.

General Reference

- * M. H. Hey, *An Index of Mineral Species and Varieties* (Brit. Museum, London), 1950, p. 171.

STRONTIANITE

Chem. Comp. $\text{SrO} \cdot \text{CO}_2$.

System. Orthorhombic.

Habit. Prismatic, acicular. Often twinned on (110), lamellar or pseudo-hexagonal.

Structure. Crystalline. Fibrous, granular.

Cleavage. Perfect \parallel (110), poor \parallel (010).

Fracture. Uneven, brittle.

Hardness. 4.

Spec. Grav. 3.7 .

Lustre. Vitreous, resinous.

Colour. Colourless, white, green, yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low for $\alpha = 1.520$, high for $\beta = 1.667$, $\gamma = 1.667$. Birefringence very strong, $\gamma - \alpha = 0.147$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. $Bxa = X = c \perp (001)$. $Z = a$. Straight extinction \parallel length in prismatic grains. $2V = 7^\circ$. $2E = 12^\circ$. Dispersion weak, $\rho < \nu$. Non-pleochroic.

Characters in Sediments. The acicular habit, contrasted R.I. values for α and γ , very strong birefringence and negative biaxial figure of small angle, help to diagnose this mineral, but its presence should if possible be confirmed by chemical tests (crimson flame of Sr and solubility in HCl). It is not a common mineral in nature, still less so in sediments.

Occurrence. In Eocene, Oligocene, Miocene-Pliocene and Pleistocene deposits, Colorado, U.S.A.¹

Possible Sources of Derivation. Mineralized veins and concretions in limestones.

Reference

- ¹ T. L. Bailey, *Univ. Texas Bull.* 2333, 1923.

SULPHUR

Chem. Comp. S.

System. Orthorhombic.

Habit. Prismatic, pyramidal, tabular. Interpenetration twins on (101) more rarely on (110) or (011).

Structure. Crystalline, massive, granular.

Cleavage. Imperfect $\parallel (001)$, (110), (111).

Fracture. Conchoidal.

Hardness. 2.

Spec. Grav. 2.06.

Lustre. Resinous.

Colour. Yellow. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\alpha = 1.957$, $\beta = 2.037$, $\gamma = 2.245$. Birefringence extreme, $\gamma - \alpha = 0.288$. Optically biaxial, positive. Optic axial plane $\parallel (010)$. $Bxa = Z \perp (001)$. $X = a$. $2V = 69^\circ$. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Native sulphur is rare in sediments (other than authigenic), but may be searched for in suitable circumstances, generally as granules, identified by colour, R.I. and form. Determinable crystals in sediments are rare. The mineral is only to be anticipated where a local and distinctive rock suite (usually volcanic) is laid under contribution to detrital sediment.

Occurrence. From Carboniferous Rocks, Texas, U.S.A.^{1,2}

Possible Sources of Derivation. Recent volcanoes. Mineral veins. Hot springs, etc.

References

- ¹ E. A. Smith, *Science*, 3, 1896, p. 657.

- ² E. M. Skeats, *Univ. Texas Mineral Survey, Bull.* 11, 1902, p. 29.

TALC

(See STEATITE, p. 187)

THORIANITE

[Pl. 39, *between pp. 176–177*]*Chem. Comp.* ThO₂.*System.* Isometric; hexoctahedral.*Habit.* In cubic crystals or penetration twins on (111).*Structure.* Crystalline.*Cleavage.* Poor || (001).*Fracture.* Uneven, occasionally conchoidal. Brittle.*Hardness.* 6.5.*Spec. Grav.* 9.7.*Lustre.* Dull metallic.*Colour.* Dark grey, brownish black, black. Opaque; translucent on thin edges.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. extreme, average $2.20 \pm$ (variable). Isotropic in thin translucent grains. Radioactive.*Characters in Sediments.* As well preserved or water-worn cubic grains or small pebbles in gem-gravels, of characteristic lustre and colour.*Occurrence.* In stream gravels, Galle district, Southern Province; in Balangoda district and near Kondrugala, Sabara Gamuwa Province, Ceylon¹; in alluvial deposits at Betroka and Andolobe, Madagascar²; in black sands, gold placer, Boshogoch River, Transbaikalia, U.S.S.R.³.*Possible Sources of Derivation.* Pegmatite veins.**REMARKS.** A geographically localized mineral not so far recorded as detrital in the United Kingdom.*References*^{1, 2, 3} J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley New York), 1955, p. 621, and refs. cited.*General Reference*C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 434.

THULITE

(VARIETY OF ZOISITE, *q.v.* p. 206)

THURINGITE

Chem. Comp. $2[(\text{Fe}'', \text{Fe}'')_{12}(\text{Si}, \text{Al})_8\text{O}_{20}(\text{OH})_{16}]$.*System.* Monoclinic.*Habit.* Massive. Aggregate of minute hexagonal (001) scales.

Structure. Crystalline.

Cleavage. Distinct \parallel (001).

Fracture. Subconchoidal.

Hardness. 2.5.

Spec. Grav. 3.15–3.19.

Lustre. Pearly or dull.

Colour. Olive green, dark green.

Mag. Prop. Weakly magnetic.

Elect. Prop. —

Opt. Prop. R.I. high, $\alpha = 1.653$, $\beta = 1.665$, $\gamma = 1.665$. Birefringence moderate, $\gamma - \alpha = 0.012$. Optically biaxial, negative. Optic axial angle and dispersion small. X near c. X = nearly colourless, Y = Z = dark green.

Characters in Sediments. In scaly green grains or aggregates somewhat resembling mica in habit.

Occurrence. In the Yorkshire Dogger (Inferior Oolite)¹.

Possible Sources of Derivation. Metamorphic rocks; garnet-bearing iron ores.

REMARKS.—A ferriferous member of the chlorite group, but relatively uncommon in sediments. Probably an alteration product; in some instances closely associated with garnet (*e.g.* Lake Superior iron region).

Reference

¹ R. H. Bastall and J. E. Hemingway, *Geol. Mag.*, **86**, 1949, pp. 201–225, 265–278.

General Reference

Loretz, *Zeit. Krist.*, **13**, 1887, p. 52.

TITANITE (SPHENE)

[Pl. 40A, B, *between pp.* 176–177]

Chem. Comp. $\text{CaO} \cdot \text{SiO}_2 \cdot \text{TiO}_2$.

System. Monoclinic.

Habit. Euhedral, prismatic, diamond- or wedge-shaped (flattened \parallel (001) and (111)). Frequently twinned on (100).

Structure. Crystalline.

Cleavage. Good \parallel (110), imperfect \parallel (100) and (112), rare \parallel (111).

Parting \parallel (221) twin lamellae.

Fracture. Irregular.

Hardness. 5–5.5.

Spec. Grav. 3.4–3.56.

Lustre. Vitreous, resinous.

Colour. Brown, brownish-yellow, orange, yellow-green, olive-green. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 1.900$, $\beta = 1.907 \pm$, $\gamma = 2.034$. Birefringence very strong, $\gamma - \alpha = 0.134$. Optically biaxial, positive. Optic

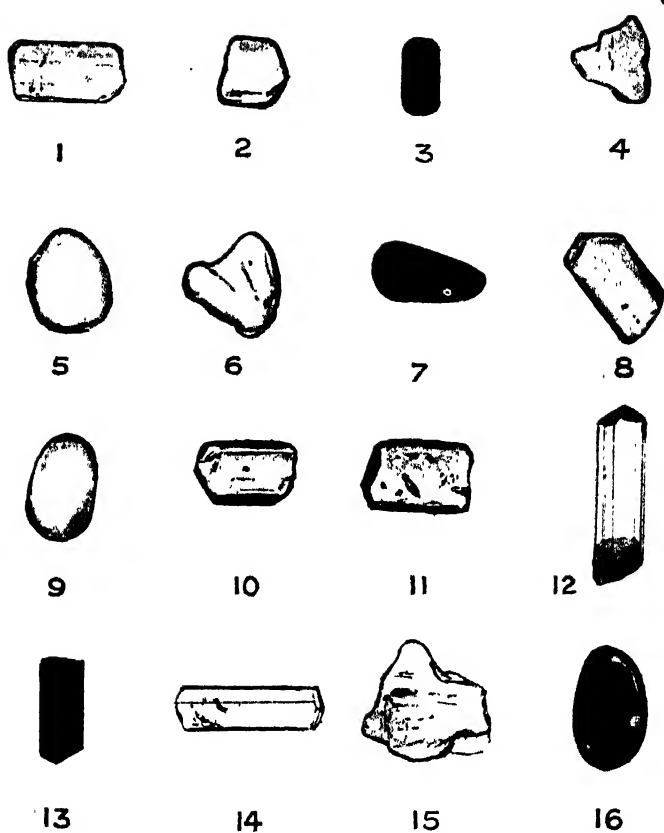
axial plane \parallel (010). $Bxa = Z$ practically \perp (102), \wedge about 51° with cleavage (c) in obtuse angle β . $Y = b$. Optic axial angle small but variable, $2V = 27^\circ \pm$. $2E = 52\frac{1}{2}^\circ$. Total extinction seldom observed with white light, colour changes being from 'ultra-blue' to yellows and reds. Very strong axial dispersion, $\rho > \nu$, usually well seen in the somewhat peculiar interference figure (with convergent light); this figure is generally incomplete in detrital grains, but the isogyres of the partial figure may prove of diagnostic value. In this connexion A. Brammall writes 'the brush is broad, merely a dark grey shadow, and is reddish on the convex side, bluish on the concave side. . . .' With Wratten light-filters . . . 'each colour applied in turn yields a sharper darker brush free from marginal colour contrasts. The approximate position of the brushes for red and green respectively can usually be fixed accurately enough to verify the dispersion formula. . . .' 'The direction of maximum absorption is "slow" and rarely the direction of elongation'¹². Occasionally pleochroic in strongly coloured varieties: X = yellow or colourless, Y = greenish pink or brownish yellow, Z = salmon pink or pale yellow.

Characters in Sediments. The commonest type of detrital titanite is, the irregularly shaped, slightly rounded or acutely ragged grain determined principally by (110) cleavage; the diamond-shaped grains, either with equidimensional margins or elongated somewhat like a tetragonal bipyramid, are also observed. Such grains have been figured by E. F. Newton¹. In colour titanite is usually brown to brownish-yellow, often with dusky interior; or the colour may appear bleached; more uncommon are the orange, yellow-green and olive-green types. Some crystals are observed to be traversed by a network of cracks due mainly to fracture, to a lesser degree to the combination of (110) and (100) cleavages. Diagnosed chiefly by the high R.I., colour, absence of extinction, interference figure and inclined dispersion, though there are many cases where positive diagnosis is difficult.

Occurrence. 'Some of the horizons at which it is relatively plentiful are the Bunter, the Keuper, the Middle and Upper Lias, the Inferior Oolite . . . the Callovian, Kimmeridgian, Portlandian, Aptian, Albian and the Eocene, Pliocene and Glacial deposits generally'². In the New Red Sandstone of the West of England³; in the Northampton Ironstone⁴; in the Upper Kimmeridge Clay and Portland Sand of Buckinghamshire, etc.⁵; in the Lower Greensand of Aspley Guise, Bedfordshire⁶ and Great Gransden, Huntingdonshire⁷; in the Sandgate Beds of Surrey⁸; in the Fuller's earth (Lower Greensand) of Nutfield, Surrey⁹; in the Red Crag, Chillesford Beds, Upper Crag and *Leda myalis* Bed. of East Anglia (Pliocene)¹⁰; in the dune sands of South Wales¹¹; in the Dartmoor detritals¹².

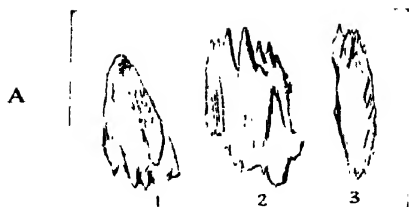
Later Records. In Downtonian, Tenbury, Worcestershire¹³; in Fell Sandstones, Lower Carboniferous, Northumberland¹⁴; in Northampton Sand Ironstone Field¹⁵; in Fuller's earth, Western Weald¹⁶.

Possible Sources of Derivation. Granites, intermediate igneous rocks, metamorphic rocks such as gneisses, schists and altered limestones. When abundant probably authigenic.



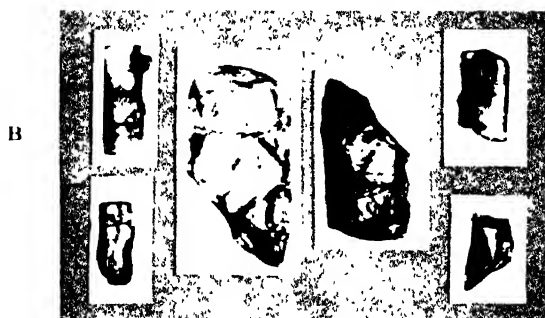
TOURMALINE.

- | | | | |
|------|---|---------|--|
| 1 3 | Tunbridge Wells Sand, Tunbridge Wells, Kent [x70] | 10 | Recent Sands, Brazil [x 70] |
| 4 | Ashdown Sand, Hastings, Sussex [x 50] | 11 | Bagshot Sand, Hampstead, London [x 40] |
| 5, 6 | Glacial Sands, Withybush, Haverfordwest, Pembrokeshire [x 40] | 12 | Moruga Sands (Pliocene), Trinidad [x 70] |
| 7 | Blown Sand, Newgale, Pembrokeshire [x 70] | 13, 14. | Pliocene Sands, St Erth, Cornwall [x 70] |
| 8 | Eocene Sand, Bromley, Kent [x 70] | 15 16 | Pliocene Sands, St Erth, Cornwall [x 40] |
| 9 | Blown Sand, Rosslare, Co. Wexford [x 40] | | |



A. TRIMOLITI

- A 1 Glacial Sand, Menai Straits (Anglesey) [x 60]
A 2-3 Glacial Sand, Haverfordwest, Pembrokeshire [x 40]

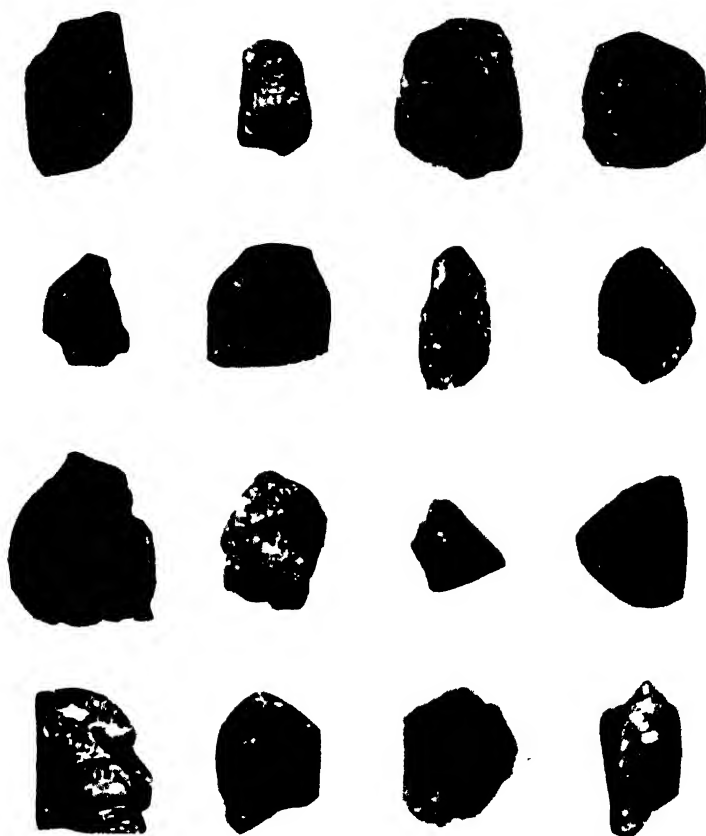


B. WOLF ASTONITI (NB Locality not known)



C. ZOISITI

- C 1-3 Miocene Sand, Santa Fe Springs Calif. U.S.A. [x 45]



XINOTIMI

Residual Cassiterite Deposits, Muntok District, N.W. Banka, Indonesia [x 40]

Occurrence. In the Millstone Grit of Yorkshire¹; in the Lower Coal Measures of South-West Lancashire²; in the New Red Sandstone of the West of England³; in the Upper Kimmeridge Clay and Portland Sand of Dorset, Wiltshire and Oxfordshire⁴; in the Chalky-Jurassic Boulder Clay at Ipswich⁵; in the Lower Greensand of the Dorking-Leith Hill district⁶; in the Cretaceous, Eocene of the Haldon Hills, Devonshire⁷; in the Suffolk Boxstones⁸; in the later Tertiary deposits of East England⁹; in the Pliocene deposits of Cornwall¹⁰; in the Plateau deposits and Beach deposits of S.E. Devonshire¹¹; in the shore sand of St. Ives Bay, Cornwall¹²; in the dune sands of South Wales¹³; in the Dartmoor detritals¹⁴.

Later Records. In Fell Sandstones, Lower Carboniferous, Northumberland¹⁵; in Lower Greensand, E. Kent¹⁶; in Beach sand, Carbis Bay, Cornwall¹⁷.

Possible Sources of Derivation. Granite, greisen and other contact metamorphic rocks.

REMARKS. Topaz is seldom an abundant mineral in detrital sediments and it tends to be local. It may sometimes be easily confused with andalusite, which it resembles in certain crystallographic and physical properties; it may be differentiated from that species by its cleavage, general absence of pleochroism, optically positive character and transparency, andalusite being so commonly clouded with alteration products and carbonaceous matter. On the other hand, where topaz has altered to damourite (hydro-mica), its distinction from sericitized andalusite is a matter of considerable difficulty.

References

- ¹ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, pp. 264, 273.
- ² A. Gilligan, *Proc. Liverpool Geol. Soc.*, 1933.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 235.
- ⁴ E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 240.
- ⁵ P. G. H. Boswell, *Journ. Roy. Anthropol. Inst.*, **63**, 1923, p. 229.
- ⁶ H. A. Hayward, *Proc. Geol. Assoc.*, **43**, 1932, p. 1.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, pp. 210, 214, 226, 227.
- ⁸ P. G. H. Boswell, *Geol. Mag.*, 1916, p. 250.
- ⁹ I. S. Double, *Proc. Geol. Assoc.*, **35**, 1924, p. 332.
- ¹⁰ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, pp. 359, 362.
- ¹¹ W. G. Shannon, *Geol. Mag.*, **64**, 1927, p. 147.
- ¹² T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 122.
- ¹³ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 325.
- ¹⁴ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 38.
- ¹⁵ D. D. Robson, *Quart. Journ. Geol. Soc.*, **112**, 1956, p. 254.
- ¹⁶ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- ¹⁷ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General Reference

- C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 435 and Pl. 28 (for alluvial topaz).

TORBERNITE

Chem. Comp. $\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$.

System. Tetragonal; ditetragonal-dipyramidal.

Habit. Tabular || (001).

Structure. Crystalline, micaceous or scaly aggregates.

Cleavage. Perfect || (001); less pronounced || (100).

Fracture. Uneven.

Hardness. 2-2.5.

Spec. Grav. 3.2.

Lustre. Vitreous; pearly on (001).

Colour. Various shades of green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\omega = 1.592$, $\epsilon = 1.582$. Birefringence moderate, $\omega - \epsilon = 0.010$. Optically uniaxial, negative. Non-pleochroic except in thick grains when $\omega =$ sky-blue, $\epsilon =$ green.

Characters in Sediments. Tabular green grains, tending to micaceous appearance.

Occurrence. In Dartmoor detritals¹.

Possible Sources of Derivation. Mineral veins associated with granite, carrying uraninite (p. 198) and copper sulphides.

REMARKS.—An extremely localized detrital mineral, normally of secondary origin, associated with autunite (p. 54) and uraninite (p. 198), of which latter species it is an oxidation product. The mineralogy of Torbernite is somewhat confused².

Reference

- ¹ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1938, pp. 46, 47.

General Reference

- ² J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, p. 981.

TOURMALINE

[Vol. I, Pl. 8A, facing p.224, and Pl. 41, between pp. 192-193]

Chem. Comp. $\text{Na}_2\text{O} \cdot 8\text{FeO} \cdot 8\text{Al}_2\text{O}_3 \cdot 4\text{B}_2\text{O}_3 \cdot 16\text{SiO}_2 \cdot 5\text{H}_2\text{O}$.

System. Trigonal.

Habit. Prismatic, often with vertical striations, irregular terminations.

Structure. Crystalline, massive, compact; frequently radiating or in parallel growth.

Cleavage. Imperfect || (11 $\bar{2}$ 0) (rhombohedral) and poor || (10 $\bar{1}$ 1). Basal parting.

Fracture. Subconchoidal.

Hardness. 7-7.5.

Spec. Grav. 2.98-3.20.

Lustre. Vitreous, resinous.

Colour. Brown, blue, green, black, brownish-black, pink; rarely colourless. Transparent, translucent and opaque (rare).

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\epsilon = 1.658$, $\omega = 1.698$. Birefringence strong, $\omega - \epsilon = 0.040$. Optically uniaxial, negative. Length fast. Occasionally grains show anomalous biaxial interference figure, when $2E = 10^\circ$. Prismatic grains give straight extinction. Pleochroism varies with colour, being normally most intense in brown varieties: ω = green, yellow-brown, blue or black $> \epsilon$ = yellow, violet or colourless. Maximum absorption in prismatic grains \perp vibration plane of polarizer.

Characters in Sediments. An ubiquitous species, occurring principally in three forms, prismatic with varied terminations, basal or quasi-basal (usually well rounded) and irregular fractured grains. The prismatic varieties may be terminated by rhombohedra and basal parting, but are often void of terminal faces, being frequently bounded by parting or irregular fracture. Pseudo-hexagonal plates flattened \parallel (0001) and modified by (11 $\bar{2}$ 0) faces have been described, but are rare; such grains and similar basal types exhibit good uniaxial interference figure. Colour and pleochroism vary greatly, the brown and dark coloured grains normally showing the strongest pleochroism; blue tourmaline (indicolite) is invariably weak in this respect. Parti-coloured brown and blue or brown and green mica-like flakes are frequent. Inclusions are often noted and may be cavities, zircon, rutile (both granules and needles), opaque particles, cassiterite, quartz, topaz, fluorite, feldspar, muscovite (gilbertite), anatase, brookite and water-clear titanite⁶. Prismatic grains often show striations \parallel principal axis. Zoning is an occasional feature (*e.g.* Dartmoor). The mineral is nearly always remarkably free from decomposition products, grains being normally translucent.

Occurrence. Ubiquitous in detrital sediments at most geologic horizons in Great Britain. A brief selection from the prolific records of this mineral covers most of the varieties: in the Bunter Pebble Bed of the West of England¹; in the New Red Sandstone of the West of England²; in the Cretaceous and Tertiary outliers of the West of England³; in the Pliocene deposits of Cornwall⁴; in the Dartmoor detritals⁵.

Later Records. In Old Red Sandstone, Comeragh Mountains, Co. Waterford, Ireland⁶; in Lower Carboniferous, Anglesey and Caernarvonshire (outgrowths)⁷; in St. Bees Sandstone, S. Cumberland and Furness⁸; in Lower Greensand, E. Kent⁹; in Lower Greensand, Western Weald¹⁰; in Beach Sand, Carbis Bay, Cornwall¹¹.

Possible Sources of Derivation. Pneumatolytic rocks, acid igneous rocks, pegmatites, schists, gneisses, phyllites.

References

¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 624

² H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, pp. 233, 234.

³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, **79**, 1923, pp. 208, 211, 213, 215, 218, 226.

⁴ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, pp. 358, 361, 363.

⁵ A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 34.

- ⁶ J. G. Capewell, *Quart. Journ. Geol. Soc.*, **112**, 1956, p. 406.
⁷ F. Smithson, *Geol. Mag.*, **91**, 1954, p. 180.
⁸ K. C. Dunham and W. C. C. Rose, *Proc. Geol. Assoc.*, **60**, 1949, p. 27.
⁹ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
¹⁰ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
¹¹ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General References

- A. Brammall and H. F. Harwood, Tourmalinization in the Dartmoor Granite, *Mineral. Mag.*, **20**, 1925, p. 319.
 C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 437 and Pl. 29 (for alluvial tourmaline and varieties).
 S. W. Alty, Some Properties of Authigenic Tourmaline from Lower Devonian Sediments, U.S.A., *Amer. Min.*, **18**, 1933, p. 351.

TREMOLITE

(AMPHIBOLE GROUP)

[Pl. 42A, between pp. 192-193]

Chem. Comp. $2\text{CaO} \cdot 5\text{MgO} \cdot 8\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Prismatic, euhedral or irregular; acicular.

Structure. Crystalline, fibrous.

Cleavage. Well developed $\parallel (110)$, more rarely $\parallel (100)$ and (010) .

Fracture. Subconchoidal, uneven, developed \perp prismatic cleavage.

Hardness. 5-6.

Spec. Grav. 3-3.3.

Lustre. Vitreous; pearly on cleavage flakes.

Colour. Colourless, white, grey, occasionally pink or mauve (manganese) or pale green (ferrous iron).

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.600$, $\beta = 1.616$, $\gamma = 1.627$. Birefringence strong, $\gamma - \alpha = 0.027$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. $Y \parallel b$, $Z \wedge c = 17^\circ \pm$. Length slow. Bxo inclined at low angle to c axis. $2V = 80^\circ$. Slight dispersion of the bisectrices in the plane (010) . Practically non-pleochroic in colourless varieties, but perceptibly pleochroic if mauve or green: $X =$ pale yellow, $Y =$ greenish-yellow, $Z =$ green. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Diagnosis of detrital tremolite rests chiefly on its 'hornblende' character *minus* the colour of that mineral, on R.I., extinction angle and birefringence; it frequently exhibits the same sort of 'ragged ends' typical of hornblende. Grey or white prismatic grains are the commonest; inclusions may be biotite or carbonaceous matter. Superficial alteration to *steatite* (p. 187) (noted with high power objective as minute powdery flakes or scales) is not uncommon. Fibrous varieties (*asbestos*) not recorded from detrital sediments.

Occurrence. In sands of Chipstead, Surrey (?Pliocene)¹; in later Tertiary deposits, East England²; in recent sands of S.W. Pembroke-shire and S. Cornwall³; in recent deposits of Pavia, etc., northern

Italy⁴; in Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California⁵; in Glacial Sands of the Menai Straits (Anglesey), of Haverfordwest, Pembrokeshire⁶; in Glacial deposits of Kimpton, Hertfordshire⁷; in Beach Sands, Cedar Point, Ohio, U.S.A.⁸.

Possible Sources of Derivation. Metamorphic rocks, crystalline schists. Metamorphosed magnesian limestone. From alteration of minerals in gabbros and peridotites; from the disintegration of serpentine.

REMARKS.—Tremolite is at first likely to be confused with diopside, but is soon distinguished from that mineral by its lower extinction angle, lower R.I. and (usually) lower interference tint; also by the general absence of inclusions frequently noted in diopside.

References

- ¹ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915–16, pp. 77, 91.
- ² I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 335.
- ³ Author's observations.
- ⁴ E. Tacconi, *Rend. R. Ist. lombardo*, ser. 2, vol. 34, 1901, p. 873.
- ⁵ R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, 11, 1927, p. 363.
- ⁶ Observations of G. M. Part and the author.
- ⁷ Observation of G. C. Flower.
- ⁸ F. J. Pettijohn and J. D. Ridge, *Journ. Sed. Pet.*, 3, 1933, p. 92.

URANINITE

Chem. Comp. UO₂.

System. Isometric, hexoctahedral.

Habit. Octahedral, cubic, less common dodecahedral.

Structure. Crystalline or massive (Pitchblende).

Cleavage. None.

Fracture. Uneven, conchoidal.

Hardness. 5–6.

Spec. Grav. 8–10 (pitchblende 6·5–8·5).

Lustre. Submetallic, pitch-like, dull.

Colour. Black, brownish-black, grey-green.

Mag. Prop. Non-magnetic.

Elect. Prop. -

Opt. Prop. Normally opaque; translucent in thin flakes when colour is green, brown or yellow. Isotropic.

Characters in Sediments. Dark brown to black, irregular shaped grains or flakes, usually coated with a lighter brown material due to alteration.

Occurrence. Beach Sand, Carbis Bay, Cornwall¹.

Possible Sources of Derivation. Hydrothermal cassiterite veins; granite and pegmatite; in sulphide mineral veins (see general references below).

REMARKS.—*Detrital* uraninite is a rare and impersistent species. In this connexion see particularly reference ¹ below. The mineral is strongly radioactive.

Reference

- ¹ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 74.

General References

- J. D. and E. S. Dana and ors., *System of Mineralogy*, 7th ed. (Wiley, New York), 1955, pp. 611-620. (Detailed description and references.)
C. F. Davidson and S. H. U. Bowrie, On Thucholite and Related Hydrocarbon-Uraninite Complexes, with a note on the origin of the Witwatersrand Gold ores, *Bull. Geol. Surv.*, **3**, 1951, p. 1.

UVAROVITE

(GARNET GROUP)

Chem. Comp. $3\text{CaO} \cdot \text{Cr}_2\text{O}_3 \cdot 3\text{SiO}_2$.

System. Isometric.

Habit. Dodecahedral (110), trapezohedral with hexoctahedral modifications. Striations on (110) faces.

Structure. Crystalline.

Cleavage. None.

Fracture. Irregular.

Hardness. 7.5.

Spec. Grav. 3.4.

Lustre. Vitreous, resinous.

Colour. Emerald green. Transparent, translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $n = 1.838$. Isotropic. Rarely anisotropic.

Characters in Sediments. Subangular and rounded dodecahedral grains (or more complex forms) are found in certain specialized sedimentary environments. Diagnosed by colour, high R.I. and general isotropism. Tendency to alter to chloritic matter.

Occurrence. In sands of the Kettleman Hills, California, U.S.A.¹.

Possible Sources of Derivation. Gneiss, serpentine, metamorphosed limestone.

REMARKS.—Uvarovite is rare. Often associated with chromite.

Reference

- ¹ M. N. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, **18**, 1934, p. 1562.

VESUVIANITE (IDOCRASE)

Chem. Comp. $2(\text{Mg}, \text{Fe})(\text{OH})_2 \cdot 2\text{Al}_2\text{Si}_2\text{O}_7 \cdot 5\text{Ca}_2\text{SiO}_4$. Beryllium may be present.

System. Tetragonal: holosymmetric.

Habit. Prismatic, pyramidal, the latter sometimes being a combination of prism (100) with (111) and (311); (110) often developed.

Structure. Crystalline, columnar or massive.

Cleavage. Indistinct || (110), poor || (100) and (001).

Fracture. Conchoidal.

Hardness. 6.5.

Spec. Grav. 3.35–3.45.

Lustre. Vitreous.

Colour. Brown, red, green, pale blue or yellow (rare). Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\epsilon = 1.705$, $\omega = 1.713$. Birefringence weak, $\omega - \epsilon = 0.008$. Optically uniaxial, negative. Rarely biaxial, with variable optic axial angle: $2E = 30^\circ - 60^\circ$. Straight extinction. Elongation fast. Pleochroism varies, $\omega > \epsilon$: in green varieties, yellow-green to colourless; in brown varieties, yellow-brown to brownish-grey; in blue varieties, dark blue to colourless; in red varieties, red to colourless or grey.

Characters in Sediments. More detrital vesuvianite is required for study before the average characteristics of this mineral in sediments can be definitely stated. Thus far observations indicate a tendency for the grains to be prismatic, brown or greenish-brown in colour, weakly pleochroic, but in all cases typified by strong relief and weak birefringence. Other optical properties vary, both uniaxial positive and negative forms, together with biaxial crystals, being observed. [N.B.—The positive form may be the variety *viluite*.] The uneven distribution of the colouring matter has been noted in one or two instances, also colour-zoning.

Occurrence. Possibly in the dune sands of South Wales¹; in superficial deposits derived from the Bodmin Granite, North Cornwall²; in Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California³; in sands on the south shore of Long Island, New Jersey⁴; in the Limburg Loess⁵.

Later Records. In sands of the Hoggar district, Central Sahara⁶.

Possible Sources of Derivation. Thermally metamorphosed limestone (in association with epidote, garnet, diopside etc.); crystalline schist; pegmatite; gneiss.

REMARKS.—*Viluite* is a rare variety of vesuvianite, containing B_2O_3 . Usually exhibits a positive biaxial interference figure.

References

- ¹ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 322.
- ² Author's observations.
- ³ R. D. Reed and J. B. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, **11**, 1927, p. 363.
- ⁴ R. J. Colony, *Journ. Sed. Pet.*, **2**, 1932, p. 150.
- ⁵ J. H. Druif, Over het ontstaan der Limburgsche Löss in verband met haar mineralogische Samenstelling, *Utrecht*, 1927.
- ⁶ H. M. E. Schurman, *Geologie en Mijnbouw, Nw. Serie*, 18e Jaargang, 1956, pp. 161–164.

VILUITE

(VARIETY OF VESUVIANITE (IDOCRASE), *q.v. supra*)

WOLFRAMITE

Chem. Comp. (Fe, Mn)O . WO₃.

System. Monoclinic.

Habit. Prismatic, bladed, tabular (100).

Structure. Crystalline, massive, lamellar, granular.

Cleavage. Perfect \parallel (010). Parting \parallel (100) and (102).

Fracture. Uneven.

Hardness. 5-5.5.

Spec. Grav. 7.2-7.5.

Lustre. Submetallic, brilliant on (010), dull on other faces.

Colour. Brown, greyish-black, black. Translucent to opaque.

Mag. Prop. Moderately magnetic (Fe-bearing variety).

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 2.26$, $\beta = 2.32$, $\gamma = 2.42$ (Li). Birefringence very strong, $\gamma - \alpha = 0.16$. Optically biaxial, positive. Optic axial plane \perp (010). $Bxa = Z \wedge c$ 17° - 21° . Optic axial angle large. Pleochroism variable: X = yellow green < Y = pale green, brown < Z = grass green, brown red.

Characters in Sediments. Generally occurs as irregular greyish-black, bladed 'metallic' grains, opaque except on thin edge, when the very high R.I. and (occasionally) strong pleochroism can be detected, the latter property being characteristic of the Mn-bearing variety (Huebnerite). In favourable circumstances (010) cleavage flakes, if sufficiently translucent, can be confirmed by the extinction angle (17° - 21°).

Occurrence. Dune sands of South Wales (?)¹; in the alluvials of the Bufumbira district, Uganda²; in the Malay Alluvium³; in black sands, Nome Creek, Alaska⁴; in recent deposits, Bodmin Moor, Cornwall⁵.

Later Records. In Beach sand, Carbis Bay, Cornwall⁶.

Possible Sources of Derivation. Mineral lodes.

REMARKS. Wolframite is really a group name comprising minerals varying in composition from FeWO₄ (ferberite) to MnWO₄ (huebnerite). Associated minerals are usually manganese and tin ores, also fluorite.

References

¹ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 324.

² A. D. Combe and W. C. Simmons, *Geol. Surv. Uganda*, **3**, 1933.

³ W. R. Dunstan, *Bull. Imp. Inst.*, **14**, 1916, p. 321.

⁴ A. S. Wilkerson, *Amer. Min.*, **15**, 1930, p. 77.

⁵ Author's observations.

⁶ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 80.

WOLLASTONITE

[Pl. 42B, between pp. 192-193]

Chem. Comp. CaO . SiO₂.

System. Monoclinic.

Habit. Tabular (100) or (001).

Structure. Crystalline. Massive.

Cleavage. Perfect \parallel (100), good \parallel (001); imperfect \parallel ($\bar{1}01$) and ($\bar{1}02$).

Fracture. Uneven.

Hardness. 5.

Spec. Grav. 2.9.

Lustre. Vitreous, pearly on cleavage faces.

Colour. Colourless, white, grey, yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.620$, $\beta = 1.632$, $\gamma = 1.634$. Birefringence moderate, $\gamma - \alpha = 0.014$. Optically biaxial, negative. Optic axial plane \parallel (010). $Bxa = X \wedge c$ at 32° in acute angle β . Elongation \parallel b. Y near b. Optic axial angle moderate: $2V = 39^\circ$. $2E = 65^\circ$. Dispersion distinct, $\rho > \nu$.

Characters in Sediments. Detrital wollastonite is determined principally by (100) and (001) cleavages. Diagnosed by careful optical measurements, in particular R.I., moderate birefringence, extinction angle and absence of pleochroism. Alteration to calcite sometimes noted.

Occurrence. In the volcanic soil of the East Indian Archipelago¹; in shore sands, Long Island and New Jersey, U.S.A.²; in the alluvial deposits of Du Toit's Pan, West Africa³.

Possible Sources of Derivation. Metamorphosed limestone.

REMARKS.- Wollastonite is often associated with calcite, diopside, epidote, garnet, zoisite.

References

¹ J. van Baren, *Contrib. Geol. Inst. Univ. Wageningen*, 17, 1931.

² R. J. Colony, *Journ. Sed. Pet.*, 2, 1931, p. 150.

³ S. Meunier, *C.R. Acad. Sci. Paris*, 84, 1877, p. 250.

XENOTIME

[Pl. 43, between pp. 192-193]

Chem. Comp. $Y_2O_3 \cdot P_2O_5$.

System. Tetragonal.

Habit. Euhedral, prismatic. Twinned on (101).

Structure. Crystalline.

Cleavage. Perfect \parallel (110).

Fracture. Uneven, irregular.

Hardness. 4-5.

Spec. Grav. 4.4-4.6.

Lustre. Vitreous.

Colour. Shades of brown, brownish-red, yellow. Translucent.

Mag. Prop. Moderately magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\epsilon = 1.816$, $\omega = 1.721$. Birefringence strong, $\epsilon - \omega = 0.095$. Optically uniaxial, positive. Length slow. Compensates $\frac{1}{2}$ length. Straight extinction. Pleochroism weak: $\omega =$ pale yellow, brownish-yellow, $\epsilon =$ yellow, green

Characters in Sediments. Usually occurs as pale yellow, orange or pink,

beautifully formed euhedra, doubly terminated tetragonal prisms; alternatively as rounded prismatic grains or as subangular rectangular flakes, in all cases exhibiting very high relief. The strong resemblance morphologically and optically to coloured zircon is invariable, and renders positive diagnosis of xenotime in detrital sediments a matter of great difficulty by microscopical means alone. The larger alluvial grains from recorded foreign localities afford the most promising material for study; these sometimes show patchy decomposition products recalling the cerium oxide films developed superficially on monazite.

Occurrence. In the Millstone Grit of Yorkshire¹; in Grindstones from the Yorkshire Coal Measures²; in the Lower Permian at Conisborough³; in the Bunter Pebble Bed of the West of England⁴; in the Lower Greensand of Great Gransden, Huntingdonshire, and of Apsley Guise, Bedfordshire⁵; in the Pliocene Sands of St. Agnes and St. Erth, Cornwall⁶; in Pleistocene deposits of the lower part of the Great Ouse Basin⁷; in beach sands, Florida, U.S.A.⁸.

(N.B.—In each of the above cases, the mineral is only recorded as a possible alternative to certain abnormal types of zircon.)

Later Records. In Beach sand, Carbis Bay, Cornwall⁹; in Residual deposits, Muntok district, N.W. Banka, Indonesia (see Pl. 43)¹⁰. (In both cases identification positive.)

Possible Sources of Derivation. Granites, pegmatites, intermediate rocks; less commonly gneiss.

REMARKS.—Xenotime is an exceedingly difficult mineral to differentiate from coloured zircon in detrital sediments by ordinary microscopical methods; recourse to spectroscopic methods is essential to its positive determination. During the last few years there has been an increasing tendency on the part of British petrographers to give coloured zircon priority of record rather than indicate a doubtful occurrence of xenotime and short of definite chemical and spectroscopic proof of this species, this policy would seem to be more in keeping with the observed facts. The extreme rarity of the mineral, or of the equivalent coloured zircon for that matter, makes research into its detrital occurrences a difficult task. The principal differences from zircon consist in its weak magnetic properties, lesser tendency to exhibit inclusions, normal absence of zoning, lower R.I. and softer nature: the latter may to some extent account for its rarity.

References

- ¹ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 267.
- ² H. P. Lewis and W. J. Rees, *Geol. Mag.*, **63**, 1926, p. 13.
- ³ A. Gilligan, *Proc. Yorks. Geol. Soc.*, **19**, 1918, p. 255.
- ⁴ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 623.
- ⁵ R. H. Rastall, *Geol. Mag.*, **56**, 1919, pp. 218, 268.
- ⁶ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, pp. 357, 360.
- ⁷ R. H. Rastall, *Quart. Journ. Geol. Soc.*, **82**, 1926, p. 116.
- ⁸ J. H. C. Martens, *Bull. Geol. Soc. Amer.*, **46**, 1935, p. 1580.
- ⁹ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.
- ¹⁰ J. W. A. Bodenhause, *Proc. Koninkl. Nederl. Akademie Van Wetenschappen—Amsterdam, Series B*, **57**, 1954, p. 322.

General References

O. A. Derby, *Mineral. Mag.*, **11**, 1897, p. 308.

In connexion with the possibility of occurrence and methods of diagnosing xenotime, see A. Brammall and H. F. Harwood, *Miner. Mag.*, **20**, 1923, p. 29. On methods of isolating and confirming xenotime in sediments, see J. Van der Lingen and A. R. E. Walker, *Trans. Geol. Soc. S. Africa*, **28**, 1925, p. 69.

G. Gastil, *Journ. Sed. Pet.*, **24**, 1954, p. 280.

ZIRCON

[Pl. 44A–C, between pp. 192–193]

Chem. Comp. $\text{ZrO}_2 \cdot \text{SiO}_2$.

System. Trigonal.

Habit. Euhedral; prismatic; bipyramidal. Prisms usually square or elongated in the direction of the principal axis, then terminated by pyramid faces (111). Twinning rare.

Structure. Crystalline.

Cleavage. Imperfect \parallel (110), poor \parallel (111).

Fracture. Conchoidal.

Hardness. 7.5.

Spec. Grav. 4.5–4.7.

Lustre. Adamantine, vitreous.

Colour. Colourless, yellow, brown, pink, mauve, purple, rarely green.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\epsilon = 1.991$, $\omega = 1.936$. Birefringence strong, $\epsilon - \omega = 0.055$. Optically uniaxial, positive. Length slow. Occasionally abnormal biaxial crystals are met with. Straight extinction. Pleochroic in thick crystals and strongly coloured varieties.

Characters in Sediments. A common species, varying considerably in form. The prevalent type of grain is colourless, prismatic (100) or (110) or both, with pyramidal terminations (111), (331), etc. Basal grains (flattened \parallel (001)) are scarce. Fractured grains are common, but sharply angular fragments are rare, zircon nearly always exhibiting a certain degree of rounding. Exceptionally, outgrowths on prismatic crystals giving a 'sawfish' type, have been described by J. A. Butterfield (reference below). Zoning is often observed and has been fully discussed by A. Brammall (reference below). The presence of inclusions, sometimes arranged parallel to the length of the crystal, at other times irregularly distributed, is a common feature. Inclusions may be fluid, glassy, negative crystals, or consist of minerals such as apatite and possibly xenotime. Inclusions within inclusions have also been observed. A. Brammall records gas-filled cavities, opaque dust in the form of stringers, clots and cloud-like suspensions, also minute zircons, monazite, hematite, quartz, apatite and rarely rutile and biotite, from the Dartmoor detritals (*op. cit.*). Occasionally the grains have a dusky appearance due to the crowding of inclusions, *not* to decomposition products. Large grains with abnormal optical properties (biaxial interference figures, low birefringence, pleochroism

and absence of inclusions) seem to be very local. Diagnosed essentially by its crystal form, high R.I., colour, inclusions and zoning (when developed).

Occurrence. Ubiquitous in detrital sediments.

Later Records. In Fell Sandstones, Lower Carboniferous, Northumberland¹; in Millstone Grit, Slaley, Northumberland²; in Millstone Grit, Ellingsring, Yorkshire³; in Middle Jurassic, N.E. Moorlands, Yorkshire (outgrowths)⁴; in Lower Greensand, E. Kent⁵; in Lower Greensand, Western Weald⁶; in mineral matter, Trinidad Lake Asphalt, Trinidad, B.W.I.⁷; in Beach sand, Carbis Bay, Cornwall⁸.

Possible Sources of Derivation. Acid and intermediate igneous rocks; less commonly crystalline schists and limestones.

REMARKS.—Zircon is one of the most fascinating minerals occurring in detrital sediments, on account of its widespread occurrence throughout the geological record and its great variation in form, colour and intimate properties. To appreciate fully its significance in any given sediment, the most careful investigation of each variety present is essential, especially if any correlation or differentiation of the sediments involved is contemplated. Point is given to these remarks by the researches of A. Brammall and H. F. Harwood on the Dartmoor zircons, to which references and also to other detailed accounts of this species, are given below. Confusion with xenotime is dealt with under the heading of that mineral, p. 202.

References

- ¹ D. A. Robson, *Quart. Journ. Geol. Soc.*, **112**, 1956, p. 254.
- ² F. Smithson, *Geol. Mag.*, **91**, 1954, p. 180.
- ³ F. Smithson, *ibid.*
- ⁴ F. Smithson, *ibid.*
- ⁵ G. A. Worrall, *Proc. Geol. Assoc.*, **65**, 1954, p. 193.
- ⁶ G. V. Wood, *Proc. Geol. Assoc.*, **67**, 1956, p. 127.
- ⁷ Author's observations.
- ⁸ C. F. Davidson and M. E. Cosgrove, *Bull. Geol. Surv.*, **10**, 1955, p. 79.

General References

- K. V. Chrustchoff, Beitrag zur Kenntnis der Zirkone in Gesteinen, *Tschermaks Min. Petr. Mitt.*, **7**, 1886, p. 862; also *Mem. Acad. Imp. Sci. St. Petersb.*, **43**, 1894.
- H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 623 and Pl. 31, Figs. 1-9.
- A. Brammall and H. F. Harwood, *Miner. Mag.*, **20**, 1923, p. 27.
- W. Mackie, *Trans. Edinburgh Geol. Soc.*, **11**, 1923, p. 200 (purple zircon).
- J. Zerndt, Über mikroskopische Zirkone aus den Karpathensandsteinen der Umgegend von Ciekowice, *Bull. Intern. Acad. polon.*, **A**, 1924, p. 219.
- P. G. H. Boswell, *Miner. Mag.*, **21**, 1927, p. 310 (distribution of purple zircon in British sediments—with many references).
- C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, p. 444 and Pl. 31 (for alluvial zircon).
- J. Zerndt, Mikroskopische Zirkone als Leitminerale, *Bull. Acad. Polonaise des Sciences et des Lettres, Serie A*, 1927, p. 363.
- A. Brammall, *Proc. Geol. Assoc.*, **39**, 1928, p. 28, Pl. 2.
- J. A. Butterfield, Outgrowths on Zircon, *Geol. Mag.*, **73**, 1936, p. 511.

ZOISITE

(EPIDOTE GROUP)

[Pl. 42C, between pp. 192–193]

Chem. Comp. $4\text{CaO} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.*System.* Orthorhombic.*Habit.* Prismatic, euhedral or irregular. Frequently striated \parallel c axis.*Structure.* Crystalline.*Cleavage.* Perfect \parallel (010); occasionally noted \parallel (100).*Fracture.* Subconchoidal, irregular.*Hardness.* 6–6.5.*Spec. Grav.* 3.25–3.37.*Lustre.* Vitreous.*Colour.* White, grey, yellowish-brown, pale green; pink or rose-red in the variety Thulite (due to Mn).*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. high (varies), $\alpha = 1.700$, $\beta = 1.703$, $\gamma = 1.718$. Birefringence moderate, $\gamma - \alpha = 0.018$. Optically biaxial, positive. Optic axial plane usually \parallel (010), but is not always in the same position: sometimes noted \parallel (001). $Bxa = Z \perp (100)$. $X \parallel c$, $Y \parallel b$, $Z \parallel a$, or $X \parallel b$, $Y \parallel c$, $Z \parallel a$. Straight extinction. In some examples the interference tint is deep blue, almost 'ultra blue' with little or no tendency to extinction in any position. $2V$ varies from 0° to 60° , being largest when the optic axial plane is \parallel (001). $2E = 0^\circ$ – 116° . Strong dispersion, $\rho < \nu$ or $\rho > \nu$. Pleochroism seen in large crystals: in the variety thulite $X =$ pink or red, $Y =$ light pink, $Z =$ yellow.*Characters in Sediments.* Occurs as almost colourless grains generally determined by (010), hence prismatic habit is common. The high R.I. and moderate birefringence, especially the deep blue colour, are characteristic, while inclusions of amphibole microlites in the form of thin, lath-shaped, green wisps, are also a feature of this species. The mineral gives straight extinction and is practically non-pleochroic in colourless grains; a delicate pink shade with tendency to a deeper red, denotes the variety thulite which has perceptible pleochroism, but not as strong as that of andalusite (when developed in the latter mineral), with which there is a possibility of confusion. Andalusite has a lower refractive index and higher birefringence than thulite and, of course, the latter species is far less common (see below).*Occurrence.* In the Portland Sands of South Wiltshire and Dorset¹; in the Huntstanton Red Rock²; in surface deposits, sands and gravels of Cambridgeshire³; in the Clyde alluvium⁴; both zoisite and thulite (?) in the dune sands of South Wales⁵; in various foreign sediments rich in epidote minerals, e.g. Miocene sands of Los Angeles basin, California, U.S.A.⁶; in beach sands between St. John's River and St. Augustine, Florida, U.S.A.⁷; in beach sands between Charleston, S. Carolina and Miami, U.S.A.⁸.*Later Records.* In Downtonian, Tenbury, Worcestershire⁹.*Possible Sources of Derivation.* Crystalline schists, metamorphosed

basic igneous rocks; possibly from *saussurite*, an alteration product of lime-soda feldspar.

REMARKS.—Zoisite is probably a far commoner detrital mineral than generally anticipated and owing to its similarity (if colourless) to other orthorhombic minerals, it is likely to be misnamed or overlooked. The variety thulite is more uncommon, though it may appear in recent sands in which the epidote species are strongly in evidence. Closely allied to zoisite is the monoclinic mineral clinozoisite (*q.v.* p. 85) whose presence in detrital sediments is probably by no means as rare as scanty records imply.

General References

- ¹ E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 251.
- ² R. H. Rastall, *Geol. Mag.*, **67**, 1930, p. 436.
- ³ R. H. Rastall, *Proc. Cambridge Phil. Soc.*, **17**, 1913, p. 132.
- ⁴ B. H. Barrett, *Trans. Geol. Soc., Glasgow*, **17**, 1926, p. 402.
- ⁵ A. Stuart, *Proc. Geol. Assoc.*, **35**, 1924, p. 325.
- ⁶ Author's observations.
- ⁷ J. H. C. Martens, *19th Ann. Rep. Florida State Geol. Surv.*, 1928, p. 130.
- ⁸ J. H. C. Martens, *Bull. Geol. Soc. Amer.*, **46**, 1935, p. 1580.
- ⁹ P. S. Walder, *Proc. Geol. Assoc.*, **52**, 1941, p. 247.

CHAPTER II

THE PETROGRAPHY OF CONSOLIDATED SEDIMENTS*

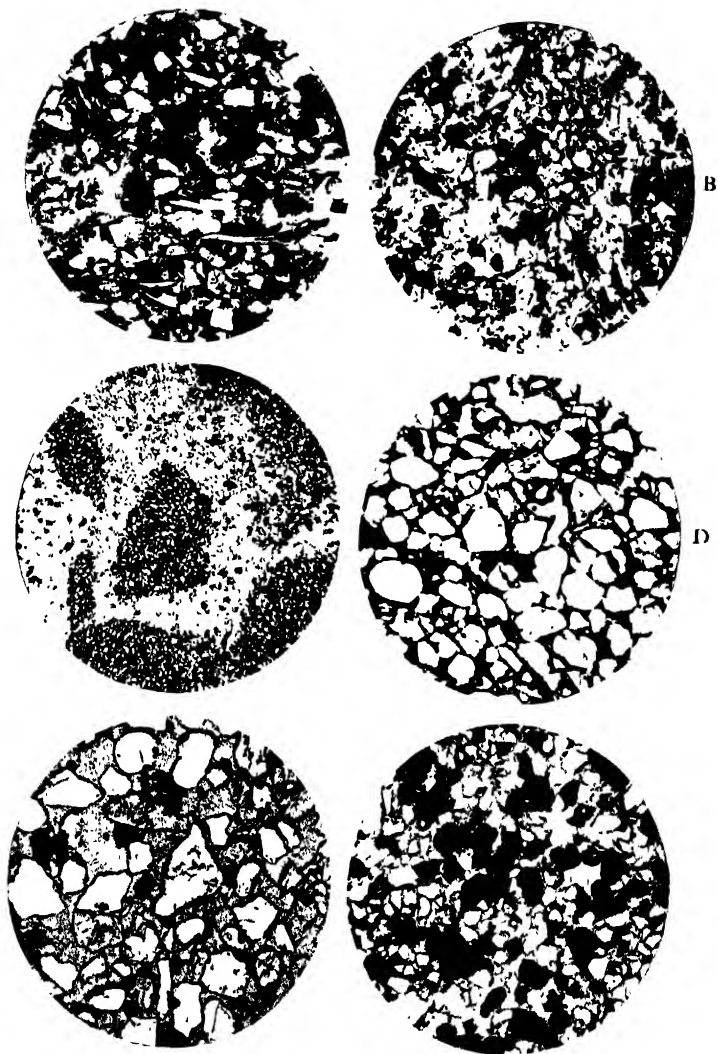
PRELIMINARY to any survey of sediments as consolidated rocks, distinct (with a few exceptions) from those composed of incoherent materials, some system of classification is essential as a basis of discussion. This task, however, is by no means an easy one, as most petrologists seem to have discovered. The difficulty of establishing a philosophical classification of sedimentary rocks is unquestionably greater than in the case of igneous rocks. No really satisfactory qualitative scheme which makes due allowance for the innumerable transitional varieties prevalent has yet been evolved; while a quantitative classification, temptingly foreshadowed by some possible adaptation of mechanical and/or statistical analysis, is still denied to the present state of knowledge.

Intimately bound up with this is the regrettably empirical nomenclature perforce adopted in the absence of something more fundamental than mere descriptive terms. In the light of modern research on both mineralogical and mechanical constitution of 'sandstones', for instance, that term *per se* has ceased to have any really precise meaning. 'Clay' is little better in this respect (though the old tendency to consider it synonymous with 'kaolin' has, in the light of modern research on clay minerals, at last been out-moded), while 'marl', 'loam' and 'silt' are notoriously subject to the loosest interpretations.

In the following paragraphs, an attempt is made to give as precise definitions and descriptions of the conventional sedimentary rock-types as are possible, based on modern intensive laboratory studies of these materials. In the present state of knowledge probably the time is hardly yet ripe for drastic revision and alteration, but the author would be failing in his duty if he did not again voice in this place that discontent which workers on sedimentary rocks have long felt in regard to classification and nomenclature.

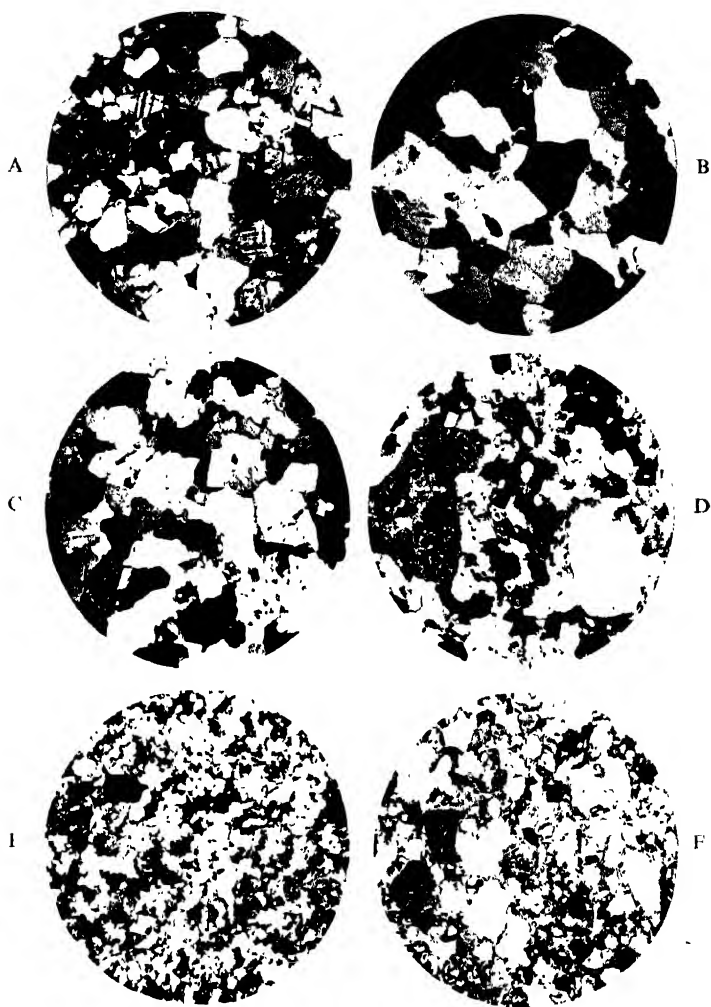
A* commendable effort was made some years back to frame generally acceptable definitions of sediments by the Committee on Sedimentation, National Research Council, U.S.A. Several

* For completeness and convenience certain semi-consolidated and incoherent raw materials, e.g. clay, ooze, abyssal mud, etc., are included in this chapter.



SANDSTONE AND GRIT

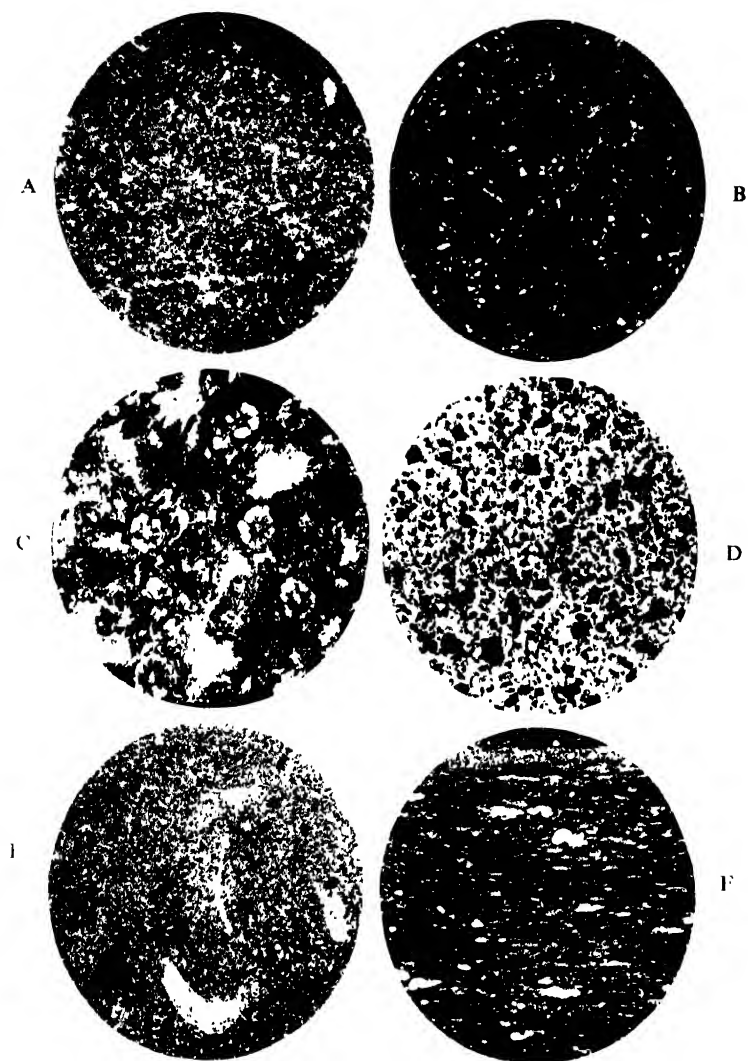
- A Hollybush Sandstone (Cambrian), Malvern [x 30]
- B May Hill Sandstone (Silurian), Malvern [x 30]
- C "Tilgate Stone", Calcareous Grit (Wealden), Sussex [x 25]
- D Ferruginous Sandstone (Aptian), Betchworth, Surrey [x 15]
- E Calcareous Grit (Aptian), Faringdon, Berks [x 25]
- F Glauconitic Grit (Selbornian), Sutton Poyntz, Dorset [x 15]



ARKOSE, QUARTZITE AND GREYWACKE.

- A Torridon Sandstone (Arkose), Loch Torridon, Ross * [x 25]
 B Quartzite (Archaean), Kentaljen, Argyllshire * [x 18]
 C Hartshill Quartzite (Cambrian), Nuneaton * [x 18]
 D Malvern Quartzite (Cambrian), Gullet Pass, Malvern [x 25]
 E Griston (Coal Measures), Sheffield, Yorks * [x 25]
 F "Greywacke" (" Carboniferous), Richmond Boring, London (1150 ft)
 [x 25]

[* Crossed Nicols]



CLAY, MUDSTONE AND SHALE

- A London Clay (Eocene), Herne Bay, Kent [x 20]
- B Fireclay (Coal Measures), Stockingtord, Nuneaton [x 25]
- C Fireclay (Coal Measures), Staffordshire with spherulitic siderite [x 13]
- D Fuller's Earth (Aptian), Surrey [x 45]
- E Mudstone (Up Tias), West Bay, Dorset [x 25]
- F Monterey Shale (Miocene), Los Angeles, Calif., U.S.A. [x 18]

A



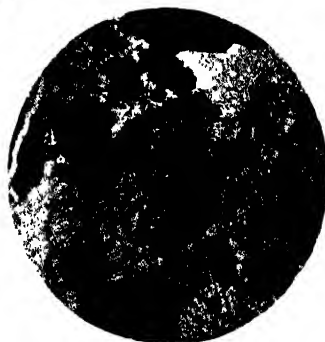
B



C



D



MARL AND LIMESTONE

- A "Chloritic" Marl, Bincombe, nr. Weymouth, Dorset [x 17]
 B Red Chalk (Marl), Hunstanton, Norfolk [x 54]
 C *Globigerina* Marl, Barbados, B.W.I. [x 39]
 D Algal Limestone (*Lithothamnion* etc.), Pemba Is., Africa [x 16]
 E Coral Limestone (Silurian), Wenlock Edge, Salop [x 20]

reports were published and in the author's opinion they served to clear the ground for generally acceptable definitions, by eliminating obsolete terms and co-ordinating international ideas then current on sedimentary petrological nomenclature¹.

In view of the importance of 'thin section' correlation of consolidated sedimentary rock-types in exploitation oil-geology, hereafter discussed, it will be found that their treatment in this volume departs from custom in its bias to the technique implied by that particular application. The rock is not merely described; it is analysed, especially in mineralogical, mechanical and *structural* detail; comparative features are stressed; contrast in specific detail rather than in group-character is emphasized.

Thin section correlation has taught at least one thing; discernment of and discrimination between the finer points of varietal characters of sedimentary rock-types. The criticism may be urged that this is carrying even intensive study too far. The reply to that is the enormous amount of successful work along these lines already accomplished in many geological laboratories and the undoubted gain to the science in consequence. Sedimentary rocks are just as worthy of minute attention to detail as their igneous counterparts; when freely accorded still more due in this respect, we may confidently expect that measure of enhanced interest in them from which advancement of knowledge, ultimately a really philosophical classification, alone can stem.

As in most branches of natural history, origin forms the soundest basis of classification and this starting point is almost universally adopted in the case of sedimentary rocks. Thus the primary division is:

(A) MECHANICAL ORIGIN (p. 211).

(B) ORGANIC ORIGIN (p. 244).

(C) CHEMICAL ORIGIN (p. 275).

¹ C. K. Wentworth and H. Williams, The Classification and Terminology of the Pyroclastic Rocks, *Bull.* **89**, *Nat. Research Council*, 1932, p. 19.

C. K. Wentworth, The Terminology of Coarse Sediments, *Bull.* **98**, *Nat. Research Council*, 1935, p. 225.

V. T. Allen, Terminology of Medium-grained Sediments, *Rep. Cmtee. on Sedimentation*, *Nat. Research Council*, 1935-1936, p. 18.

W. A. Tarr, Terminology of the Chemical Siliceous Sediments, *Cmtee. on Sedimentation*, *Nat. Research Council*, 1936.

W. H. Twenhofel, Terminology of the Fine-grained Mechanical Sediments, *Rep. Cmtee. on Sedimentation*, *Nat. Research Council*, 1936-1937, p. 81.

CLASSIFICATION OF SEDIMENTARY ROCKS

GROUP CHARACTER.		TYPES	
A. MECHANICAL ORIGIN	A1. Rudaceous	{A1. 1	Conglomerate (p. 212).
		{A1. 2	Breccia (p. 213).
	A2. Arenaceous	{A2. 1	Sandstone (p. 216).
		{A2. 2	Grit (p. 218).
		{A2. 3	Arkose (p. 220).
		{A2. 4	Quartzite (p. 221).
		{A2. 5	Ganister (p. 222).
		{A2. 6	'Greywacke' (p. 223).
		{A2. 7	Siltstone (p. 224).
	A3. Argillaceous	{A3. 1	Clay (p. 227).
		{A3. 2	Fireclay (p. 231).
		{A3. 3	Fuller's earth (p. 232).
		{A3. 4	Aeolian Clay (p. 233).
		{A3. 5	Abyssal Clay (p. 234).
		{A3. 6	Volcanic Clay (p. 236).
		{A3. 7	Residual Clay (p. 237).
		{A3. 8	Mudstone (p. 239).
		{A3. 9	Shale (p. 240).
	AB. Calcareo-Argillaceous	{AB. 1	Marl (p. 242).
		{AB. 2	Calcareous Shale (p. 243).
B. ORGANIC ORIGIN	B1. Calcareous	{B1. 1	Limestone (p. 245).
		{B1. 2	Dolomitic Limestone (p. 250).
		{B1. 3	Oolite and Pisolitic Limestone (p. 251).
		{B1. 4	Abyssal Ooze (p. 253).
		{B1. 5	Chalk (p. 254).
	B2. Siliceous	{B2. 1	Chert and Flint (<i>in part</i>) (p. 256).
		{B2. 2	Abyssal Ooze (p. 257).
		{B2. 3	Siliceous Earth (p. 258).
	B3. Ferruginous	{B3.	Ferruginous Deposits (p. 260). see also under (C2) (p. 278).
	B4. Carbonaceous	{B4. 1	Peat (p. 262).
		{B4. 2	Lignite (p. 263).
		{B4. 3	Coal and Anthracite (p. 264).
		{B4. 4	Cannel and Torbanite (p. 267).
		{B4. 5	Oil Shale (p. 268).
		{B4. 6	Asphalt, Asphaltic Bitumen and Bituminous Impregnations (p. 269).
	B5. Phosphatic	B5.	Phosphate (p. 273).

C. CHEMICAL ORIGIN	C1. Calcareous	{ C1. 1	Calcium Carbonate: Calcite (p. 277).
		{ C1. 2	Dolomite (<i>in part</i>) (p. 277).
	C2. Ferruginous	{ C2. 1	Bedded Iron-Ores (p. 279).
		{ C2. 2	Bog Iron-Ore (p. 281).
	C3. Siliceous	C3. 1	Siliceous Sinter (p. 282).
	C4. Saline	{ C4. 1	Chlorides (p. 283).
		{ C4. 2	Sulphates (p. 284).
		{ C4. 3	Nitrates and Borates (p. 286).

(A) MECHANICAL ORIGIN

This implies the action of gravity and/or transport by wind, water or ice with subsequent deposition. The predominant character is initially incoherency, the individual particle varying from the ultra-microscopic or colloidal, to the largest boulder, subsequently (with the process of time) consolidation by various cementing media. Raw materials are essentially pre-existing rock-debris released during the normal progress of erosion. These are the 'derived' or 'allogenic' constituents ('allothigenous' of some authors). The cementing media, products of mineral destabilization, organic or chemical agency, operate during or subsequent to the deposition phase; these are the 'authigenic' constituents ('authigenous' of some authors).

Rocks in this category may be subdivided into three groups on the basis of average grade-size, *i.e.* major dimension or diameter of predominant rock-fragment or particle (Vol. I, Ch. IV).

(A1) RUDACEOUS (p. 211).

(A2) ARENACEOUS (p. 215)

(A3) ARGILLACEOUS (p. 225).

(A1) RUDACEOUS DEPOSITS. These include rocks composed of 'granules', 'pebbles', 'cobbles' or 'boulders' (Vol. I, Ch. IV, p. 180) *i.e.* materials exceeding 2 mm. in grade-size of predominant constituent. Talus and cliff debris, avalanche material ('colluvial' deposits of G. P. Merrill), scree, shingle and gravel contribute the aggregates which, on consolidation, form either of two rock-types:

(A1.1) Conglomerate (p. 212).

(A1.2) Breccia (p. 213).

(A1.1) CONGLOMERATE

**Def.* A cemented clastic sediment composed of rounded fragments of pre-existing rock ranging in grade-size from pebbles to boulders (see Vol. I, Ch. IV, p. 180).

Lith. Appearance of consolidated gravel. Bedding rare or absent. Colour variable, determined largely by matrix.

Text. Coarse. Matrix fine (cryptocrystalline), or sandy.

Shape. R to SA (ellipsoidal) pebbles.

Min. Comp. Al. Pebbles of quartz, quartzite, vein-quartz, chalcedonic silica, flint, chert; occasionally other rocks, *e.g.* limestone, including also igneous rocks. Accessory minerals scarce, usually absent from matrix, recoverable from pebbles by crushing.

Au. Silica, limonite, hematite; less commonly calcite, dolomite. Cement not only binds pebbles together, but sometimes penetrates cracks in them.

Mech. Comp. Minimum grade > 2 mm. Usual types 0.75–2.5 cm. Generally variable.

Micro. Study relationship of pebbles to matrix; note boundary and whether both are in optical continuity (rare) or not; matrix normally fills interstices completely, especially in finer varieties. Quartz pebbles may be clear or turbid with inclusions: the latter are significant and may indicate origin (p. 428); undulose extinction due to strain sometimes noted. Chert generally exhibits aggregate polarization; flint is usually cryptocrystalline or optically inert. Silica cement usually cryptocrystalline, but may be slightly coarser towards centre of interspace. Presence of calcite shown by 'twinkling' and contrasted interference colour. White mica characteristic of some varieties. Presence of dolomite usually inferred from chemical test. Matrix may be contaminated with finer detritus, volcanic dust, also with minerals, *e.g.* pyrite, gold.

Types. Cambrian conglomerate of quartz, quartzite, felsite, schist, granite, etc., of Pre-Cambrian origin in siliceous and ashy matrix, St. Davids, South Wales¹; the Bunter Pebble Bed, with chocolate-coloured quartzite, Carboniferous Limestone, purple grit and volcanic rocks in siliceous or calcareous matrix, Midland counties²; 'Dolomitic Conglomerate', chiefly Carboniferous Limestone pebbles from

* In order to abbreviate and systematize descriptions, rock-types are discussed under specific property 'headings'. *Def.* = short definition. *Lith.* = lithology, *i.e.* appearance to the naked eye, megascopic characters, macro-structure, colour, etc. *Text.* = texture, either of whole rock if uniform, or of prominent components and matrix. *Shape* has reference to shape of predominant constituents expressed as R, rounded, SA, subangular, or A, angular. *Min. Comp.* = mineralogical composition, divided into *Al.*, allogenic and *Au.*, authigenic constituents. *Mech. Comp.* = mechanical composition (limiting grades for the type are given). *Micro.* = microstructure as determined from microscopical study of thin sections. *Types*, usually of British origin, are cited to illustrate the rock under discussion; the selection has been specially made from accessible occurrences in order that the student, if he wishes, may easily collect or otherwise acquire such representative examples for study. Appropriate references (*Refs.*) are added.

2 in. up to boulders, 3 ft. in diameter, set in a calcareo-dolomitic cement, of the Mendip and Bristol area (Trias)³; Eocene 'pudding stone' of Hertfordshire and Kent, mostly quartz pebbles in crypto-crystalline, siliceous matrix. (Fig. 43)⁴.

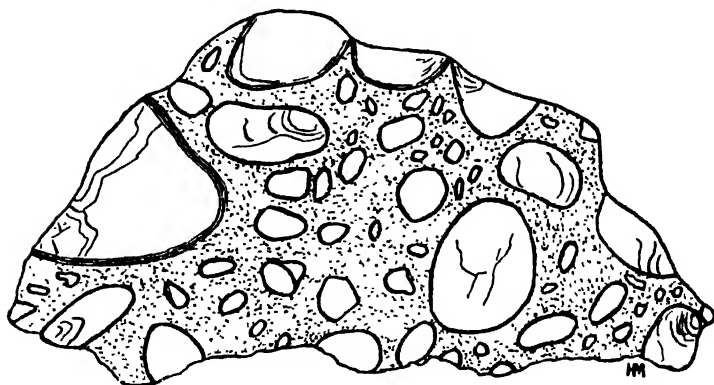


FIG. 43. Drawing of smooth surface of Flint Conglomerate (Hertfordshire 'Pudding Stone'). [$\frac{1}{2}$ Nat. Size.]

References

- ¹ H. Hicks, *Quart. Journ. Geol. Soc.*, **27**, 1871, p. 386.
- ² T. G. Bonney, *Quart. Journ. Geol. Soc.*, **56**, 1900, p. 287.
- ³ A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, p. 366.
- ⁴ J. Hopkinson, *Geol. Assoc. Jubilee Vol.*, 1910, p. 16.

General References

- J. W. Gregory, *Geol. Mag.*, **52**, 1915, p. 447.
- R. M. Field, A preliminary paper on the origin and classification of intra-formational conglomerates and breccias, *Ottawa Nat.*, **30**, 1916, pp. 29, 47, 58.
- A. Hadding, The pre-Quaternary Sedimentary Rocks of Sweden, II, The Palaeozoic and Mesozoic Conglomerates of Sweden, *Lunds Univ. Arsskrift*, **23**, 1927, p. 42.
- W. H. Twenhofel, *Treatise on Sedimentation* (Baillière, Tindall and Cox, London), 1932, p. 201.

(A1.2) BRECCIA

Def. A clastic sediment comprising angular pre-existing rock fragments, usually of varied composition and grade-size, cemented by siliceous, calcareous or other secondary medium.

Lith. Rock-fragments of distinctive shape and miscellaneous size set in a matrix of mixed character and composition. Fragments may be of the same rock or dissimilar according to uniformity or variation of parent-rocks. Bedding rare. W. H. Norton* recognizes four megascopic types: 'crackle breccia', representing incipient brecciation, with

* W. H. Norton, *Journ. Geol.*, **25**, 1917, p. 161.

fragments parted by fission-planes, but subject to little or no displacement; such fragments 'match' along their opposed sides; matrix confined to interstices and is usually of chemical origin. The '*mosaic*' type has its fragments largely disjointed and displaced. '*Rubble breccia*' exemplifies the type 'in which no matching fragments are parted by initial planes of rupture. The fragments are close-set and in touch'. The '*breccia of sporadic fragments*' is the type in which the matrix preponderates over fragments which are 'like plums in a pudding'. Where the matrix is bedded, the breccia belongs to the '*endostratic*' type, of which some of the Permian 'breccia sandstones' are examples*. In the fossiliferous breccias, fossils may occur both in fragments and in matrix, but usually the latter. Contemporaneous brecciation with deposition gives rise to '*intraformational breccias*' (C. D. Walcott).

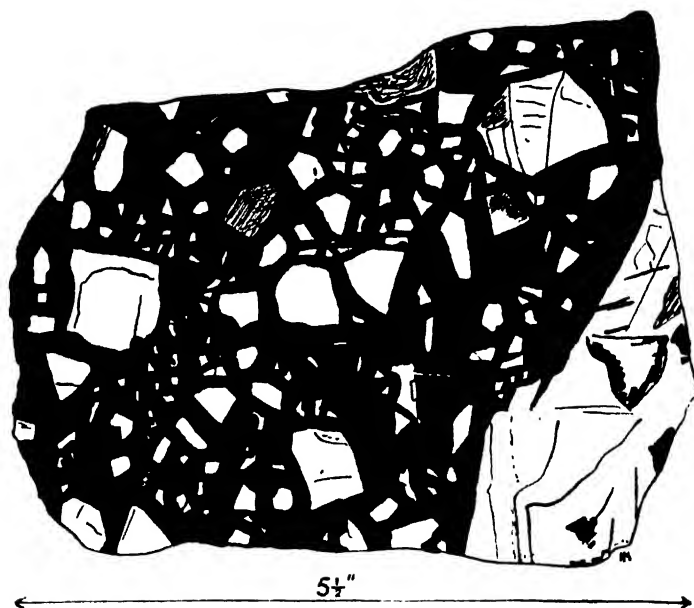


FIG. 44. Breccia with calcite fragments, etc.

Text. Coarse, determined by the size of the fragments. Matrix usually fine, like mud, or gritty.

Shape. A. Fragments sometimes show signs of attrition acquired during local transport. Particles in matrix both A and SA.

Min. Comp. Al. Any rock-type is likely to contribute, given the requisite conditions; even the softest rocks may, as fragments, survive in breccias in which little or no transport has been involved.

Au. Matrix may be composed of pulverized rocks represented as

* W. W. King, *Quart. Journ. Geol. Soc.*, 55, 1928, p. 97.

fragments, or may be of different origin; fine silt or mud; chemical deposit, *e.g.* calcite, limonite. Usually very mixed in composition.

Mech. Comp. Minimum grade > 2 mm. Usual types 0.5–3.0 cm., maximum length of fragment; but much larger fragments may occur, even huge blocks weighing several tons each. Matrix composed of particles < 0.01 mm. in the finest muddy types, ranging up to 1 mm. in the gritty types.

Micro. Study relationship of fragments to matrix; note boundaries and extent to which matrix forms seams or fills interspaces. Proportion of matrix to fragments important; in some types the latter predominate, in others the matrix is more conspicuous than the fragments see (Fig. 44). Diagnose coarse constituents and note variety of rock-types represented; if one predominating type is found, note to what extent its characteristic minerals have contributed to the matrix. Composite or simple character of the fragments also important. Examine matrix for rock-particles and individual minerals, also for alteration products and special cementing media of chemical origin. Cementing materials, where contaminated with rock-powder, usually require long and careful scrutiny to establish complete diagnosis. Shell-fragments noted in fossiliferous varieties.

Types. Permian breccias in the Penrith Sandstone, Eden Valley, Cumberland, etc., 'The Brockrams'; one type (lower) is made up of Carboniferous Limestone fragments in a red sandy matrix; the other (upper) contains fragments of basal Carboniferous conglomerate reinforced by Ordovician rocks, vein-quartz, etc.¹ Upper Permian breccias of the Midlands, 'Trappoid Breccias', in which the fragments are mainly of volcanic origin (old field-term 'trap'), with quartzites, sandstone and limestone of Pre-Cambrian, Cambrian, Ordovician and Silurian origin². Pleistocene breccias, Severn Estuary³.

References

¹ A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, p. 337.

² W. W. King, *loc. cit.*

³ L. S. Palmer, *Proc. Geol. Assoc.*, **45**, 1934, p. 145.

General References

W. H. Norton, *Journ. Geol.*, **35**, 1917, p. 161.

S. H. Reynolds, *Geol. Mag.*, **65**, 1928, p. 97.

(A2) ARENACEOUS DEPOSITS. These are the true clastic accumulations and include sands, sandstones, silts, etc., the predominant constituents of which fall between the size-limits 0.01 and 2 mm. (Vol. I, Ch. IV, p. 179); conventional silt grade-limits are 0.1–0.01 mm.; the consolidated form, siltstone, is sometimes separated as a distinct group*. Since, however, this constitutes a specific rock-type rather than a group comparable in importance with other mechanically-formed deposits (A1, A3), it is here classified under

* G. W. Tyrrell, *Principles of Petrology* (Methuen, London), 1926.

arenaceous deposits. The raw materials are essentially sand, rain-wash, etc., and these on consolidation give rise to the following types:

- (A2.1) Sandstone (p. 216).
- (A2.2) Grit (p. 218).
- (A2.3) Arkose (p. 220).
- (A2.4) Quartzite (p. 221).
- (A2.5) Ganister (p. 222).
- (A2.6) 'Greywacke' (p. 223).
- (A2.7) Siltstone (p. 224).

(A2.1) SANDSTONE

[Pl. 45A-D, *between pp.* 208-109]

Def. An arenaceous rock composed substantially of detrital quartz grains, subangular to rounded in shape, ranging from 0.1-2 mm. in grade size and cemented with siliceous, calcareous, ferruginous or other authigenic medium.

Lith. Compounded essentially of derived quartz grains cemented by a matrix which may or may not be conspicuous. Predominantly siliceous, the purest varieties containing over 99.5% SiO_2 . Bedding usually apparent, thin (laminae) or thick, either regular, horizontal, or current- or cross-bedded. Colour determined largely by nature of cementing medium, the commonest being limonite (brown), hematite (red); highly siliceous types are white to colourless. Organic components common, often casts. Structural features include ripple-marks, veining, cross-joints, organic markings, rain-prints, sun-cracks, etc.

Text. Coarse (0.5-2 mm.), medium (0.25-0.5 mm.), and fine (0.1-0.25 mm.).

Shape. Generally SA (water-worn grains); R in wind-blown sand; A in glacial sand. Predominantly angular in Grit, A2.2.

Min. Comp. Al. Quartz, muscovite, feldspar (see under Arkose, A2.3, p. 220); occasionally rock-particles of igneous or volcanic origin; accessory minerals such as ilmenite, magnetite, zircon, tourmaline, garnet, rutile, etc.

Au. Cementing materials include siliceous, ferruginous, calcareous, argillaceous and carbonaceous matter, in that order of normal occurrence. More rarely barite.

Mech. Comp. Size-limits are 0.1-2 mm. ('sand grade'); average about 0.2 mm. If the sand is superfine (= coarse silt) the lower limit is 0.05 mm.

Micro. Study quartz grains for shape, grading (uniform or mixed), degree of preservation of crystallization (euhedrism), inclusions (p. 172) and optical character, *i.e.* whether normal or undulose extinction. Muscovite detected by its irregular flaky character, cleavage

and interference colours (pinks, greens and yellows). Other prominent constituents, *e.g.* glauconite, should present no difficulty; accessory minerals best investigated by crushing and concentration (Vol. 1, Ch. III, p. 127). Quartz grains may be mutually interferent, with little or no cementing matter, when the rock approximates to the quartzite type (A2.4); in most examples the matrix is clearly discernible and limonite, hematite, calcite, silica, etc., will be easily determined. Differentiate between types in which each quartz grain is completely surrounded by cement; in which grains occur in clusters, many touching, the cement being haphazardly distributed; and those in which there is apparently more cement than derived matter. Relation of grains to cementing medium, especially peripheral contact, is important. Secondary outgrowths of silica from original quartz nuclei, each outgrowth being in optical continuity with its nucleus, are sometimes observed. Siliceous cement may be cryptocrystalline or microcrystalline. It is seldom that only one material constitutes the cement; calcite is detected by 'twinkling', hematite and limonite by colour, likewise carbon. Calcareous cement may be anticipated where organisms prevail. Greenish cement is not necessarily due to glauconite, but more often to chloritic matter after ferromagnesian minerals. Clayey matter gives rise to a dirty brown, almost indecipherable cement, though usually micaceous. Gypsum, barite, dolomite, are uncommon authigenic constituents, but are not hard to identify.

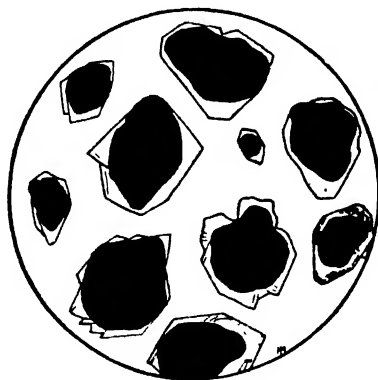


FIG. 45. Grains from the Penrith Sandstone (Permian), Cumberland, showing secondary outgrowths of quartz. [$\times 25$.]

Types. Hollybush Sandstone (Cambrian) of Malvern, etc., a mica-glauconite-bearing rock¹; Bala Sandstone of the Welsh Borders (Ordovician), a ferruginous, micaceous type with many shell-casts; Old Red Sandstone, Herefordshire and South Wales, with hematite cement²; Permian Sandstone, Penrith, Cumberland (Fig. 45), with beautiful crystal outgrowths in optical continuity with nuclei (desert sand)³; Triassic Sandstone, Alderley Edge, Cheshire, with barite

cement and impregnations of azurite, malachite, galena etc.⁴; Ash-down Sand (Wealden), Fairlight, Sussex, pure white 'glass' sandstone⁵; Lower Greensand, Faringdon, Berkshire, with glauconite, sponge remains and calcite 'platy' cement enveloping sand grains in 'ophitic' fashion⁶; Lower Greensand, Ightham, Kent ('Ightham Stone'), with radial, chalcedonic cement enclosing grains⁷; Lower Greensand ('Carstone'), Hunstanton, Norfolk and Yorkshire, with heavy ferruginous cement and oolitic grains of iron-ore with siliceous skeleton (on treatment with acid)⁸; Upper Greensand, Sutton Poyntz, Dorset, glauconitic sandstone (glauconite casts of *foraminifera*) with siliceous and calcareous cement⁹; Eocene Sandstone ('Sarsens'), chalk downs of Wiltshire, Dorset, etc., fine micaceous rock graduating to quartzite type¹⁰; Bagshot Sand, Studland, etc., Dorset, deep reddish-brown, ferruginous sandstone and variegated types¹¹.

References

- ¹ G. S. Sweeting, *Proc. Geol. Assoc.*, **38**, 1927, p. 552.
- ² A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 489.
- ³ A. Harker, *Petrology for Students* (University Press, Cambridge), 1954, p. 198 and Fig. 72, F.
- ⁴ J. W. Judd, *Quart. Journ. Geol. Soc.*, **40**, 1884, p. 749.
- ⁵ P. G. H. Boswell, *British Resources of Sands for Glass-Making* (Longmans, Green, London), 1918, p. 52.
- ⁶ Author's observations.
- ⁷ T. G. Bonney, *Geol. Mag.*, 1888, p. 297.
- ⁸ H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, **20**, 1926, p. 349; also A. Harker, *op. cit.*, p. 212.
- ⁹ Author's observations.
- ¹⁰ H. B. Woodward, *Geol. Assoc. Jubilee Vol.*, 1910, p. 304; for Upper Cretaceous sandstones of England, see W. Hill, *Mem. Geol. Surv., Cret. Rocks Brit.*, vol. 1, 1900, ch. xxv.
- ¹¹ Author's observations.

General References

- L. Cayeux, *Structure et Origine des Grès du Tertiaire parisien* (Masson, Paris), 1907.
 Les roches sédimentaires de France: Roches Siliceuses, *Mem. pour servir à l'explication de la carte géologique détaillée de la France*, Paris, 1929.
 A. Hadding, The pre-Quaternary Sedimentary Rocks of Sweden, III Palaeozoic and Mesozoic Sandstones of Sweden, *Lunds Univ. Arsskrift*, **25**, 1929.
 W. H. Twenhofel, *Treatise on Sedimentation* (Baillière, Tindall and Cox, London), 1932, p. 218.

(A2.2) GRIT

[Pl. 45E, F, between pp. 208–209]

- Def.** Restricted to an arenaceous rock composed substantially of detrital quartz grains of predominantly angular shape, ranging from 0.1–2 mm. in grade size and cemented with siliceous, calcareous, ferruginous or other authigenic medium.
- Lith.** The separation of this type from normal sandstone depends on the angularity of the quartz particles, a feature not always apparent

from megascopic examination. Every gradation from grits, in which the particles are equidimensional, through pebble-grits, to conglomerates (A1.1) is met with. In the coarse varieties prominent constituents are identifiable with the naked eye (chiefly quartz, quartzite). Stratification normally developed on a large scale and may not be apparent in the hand-specimen. Colour variable but usually yellow, buff, brown or grey. Organic remains may be present in the medium and fine varieties, less frequently in the coarse types. Prominent pebbles should be extracted and dealt with separately.

Text. Coarse to medium.

Shape. A.

Min. Comp. *Al.* Quartz; composite grains of quartz and felspar, muscovite, particles of igneous, volcanic and metamorphic origin; also of the harder sedimentary rock-types; quartzite; vein-quartz. Stable accessory 'heavy' minerals.

Au. Siliceous, calcareous, ferruginous and argillaceous cements; the first two materials are commonest. Micaceous and chloritic matter often prevalent.

Mech. Comp. Size-limits of derived particles in true grits fall between 0.1–2 mm. Above the latter grade the rock passes into a fine conglomerate (*q.v.*). Many types described as grits are mechanically classifiable under the latter heading, especially when pebbles occur.

Micro. Microscopical examination reveals at once the angularity of the predominant grains, though some degree of rounding is nearly always apparent. Inclusions in the quartz grains noteworthy. Most examples show mixed composition and present interesting problems in the identification of components. In certain calcareous grits 'lustre-mottling' is a striking feature, sometimes seen in the hand-specimen, but more conspicuous in thin section. 'When the polarizer is in position . . . the differential relief ("twinkling" effect) characteristic of the rhombohedral carbonates resolves the field into areas within each of which the calcite cementing the quartz grains is in crystallographic continuity . . . lustre-mottling . . . is due to the reflection of light from the calcite cleavages which are differently orientated'⁶. Other points in diagnosis as for Sandstones (*q.v.* p. 216).

Types. Ingletonian Grit of Yorkshire, with grains of gneiss, lava, etc., in addition to quartz, felspar, mica¹; Watch Hill Grit (Bala) of Cumberland, with vein-quartz, carbonaceous shale, spilosite, composite quartz-felspar fragments, schist and granophyre (from Carrock Fell complex) with quartzose, feldspathic, micaceous and silty matrix²; Staddon Grits (Devonian) of South Devonshire etc., purplish-red, with siliceous and calcareous cements³; Millstone Grit of Yorkshire, notable specially for quartz inclusions, pebbles and accessory minerals⁴; Inferior Oolite ('Moor Grit'), Yorkshire, tending to quartzite type⁵; 'Tillgate Stone' (calcareous grit with 'lustre-mottling'), Wadhurst Clay (Wealden), Sussex⁶.

References

- ¹ R. H. Rastall, *Proc. Yorks. Geol. Soc.*, 16, 1906, p. 94.
- ² J. F. N. Green, *Proc. Geol. Assoc.*, 28, 1917, p. 21.

³ W. G. Shannon, *Proc. Geol. Assoc.*, **39**, 1928, p. 144.

⁴ A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 251.

⁵ A. Harker, *Petrology for Students*. (University Press, Cambridge), 1954, p. 202.

⁶ G. S. Sweeting, *Proc. Geol. Assoc.*, **36**, 1925, p. 413.

N.B.—“*Pea Grit*,” “*Trigonia Grit*” etc., are *not* true grits (p. 251).

(A2.3) ARKOSE

[Pl. 46A, *between pp.* 208–209]

Def. A sandstone or grit in which detrital feldspar is a permanent constituent (25% or more). Implies derivation from granite, gneiss, etc., containing abundant feldspar.

Lith. Comparable with either sandstone or grit, generally the latter. A type separated to designate a feldspathic sandstone or grit derived from granitoid or gneissic rocks and containing prolific feldspar, the latter usually only determinable under the microscope. Colour often pale red or purple, but may vary. White mica usually prominent.

Text. Coarse to medium.

Shape. A to SA.

Min. Comp. *Al.* Quartz, feldspar (microcline, orthoclase, plagioclase, micropertthite, etc.), muscovite; rock-fragments of miscellaneous origin; iron-ores and stable accessory minerals.

Au. Siliceous, calcareous, feldspathic, hematite and limonite; greenish colour due to chlorite minerals and/or epidote; occasionally carbonaceous.

Mech. Comp. As for sandstone and grit (*q.v.*).

Micro. The chief study in these rocks is the feldspar, of which microcline and oligoclase appear to be the commonest constituents. Note relative proportions of quartz and feldspar grains. Determine carefully the optical properties of the feldspars present. Much of the quartz may show strain-polarization effects. Quartz and feldspar grains may be in mutually interferent aggregates surrounded by cementing medium, or each grain may be enveloped in a thin film of iron oxide; in the less coloured varieties, silica and/or calcite cement is common. Arkoses generally approximate to the quartzite type (A2.4) and are highly siliceous. Nature and degree of distribution of derived grains in cement important and diagnostic. Other criteria as for sandstone, grit.

Types. Torridonian rocks of the N.W. Highlands, with various feldspars, distinctive quartz and pebbles of more ancient rocks¹; Millstone Grit of Yorkshire².

References

¹ J. L. H. Teall, *Geology of the N.W. Highlands*, *Mem. Geol. Surv. Great Britain*, 1907, ch. xvi (an excellent and exhaustive account of this rock-type).

² A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 251.

General References

D. C. Barton, *Journ. Geol.*, **24**, 1916, p. 417.

- A. Hadding, The pre-Quaternary Sedimentary Rocks of Sweden, II Palaeozoic and Mesozoic Sandstones of Sweden, *Lunds Univ. Arsskrift*, 25, 1929, p. 151. (Account of the *sparagmites* of Scandinavia.)
 R. D. Reed, Geology of California, Tulsa, Oklahoma, *Amer. Assoc. Petrol. Geol.*, 1933.

(A2.4) QUARTZITE

[P1. 46B-D, between pp. 208-209]

Def. A normal sandstone or grit in which the detrital quartz is cemented by secondary silica, often in optical continuity; or a metamorphosed, recrystallized sandstone composed essentially of quartz.

Lith. Distinguish from quartzite of metamorphic origin. The sedimentary type consists almost exclusively of quartz grains set in a siliceous cement. Normally a pale-coloured, close-grained or 'sugary' rock of obvious siliceous character. Impurities may be rock-fragments visible to the naked eye, ferruginous matter, mica, etc. Quartz is often water-clear. Bedding generally only apparent on a large scale. Organisms not common.

Text. Coarse to medium; in special types, very fine (*cf.* A2.2, p. 219).

Shape. SA.

Min. Comp. *Al.* Quartz, subordinate feldspar, mica, few accessory minerals.

Au. Silica, sometimes with finely disseminated iron oxide; less commonly carbonaceous and silty matter.

Mech. Comp. Average of many examples shows detrital grains of grade-size 0.2-0.3 mm., *i.e.* of medium grade.

Micro. Under the microscope quartzites present characteristic mosaic, often granular appearance, the quartz grains closely set in a clear siliceous cement; with passage of the rock to less pure sandstone, the grains tend to be more scattered and the cement more prominent. In some examples the cementing medium develops directly from detrital nuclei by crystalline outgrowths, sometimes in optical continuity. Occasionally cement is clouded by finely divided silty matter or dust; calcite not common. White mica prevalent and, in certain cases, feldspar in sufficient quantity to designate the rock an arkose. Note particularly the size and shape of the quartz grains, any inclusions, unusual optical properties, also the relationship of grains to matrix. Distinguish sedimentary quartzite from metamorphosed sandstone by the fact that in the latter there is practically no differentiation of detrital grains and matrix, the whole being a homogeneous quartzose rock of mutually interference quartz pellicles.

Types. Pre-Cambrian quartzite, Islay, Jura, etc., Argyllshire, fine-grained saccharoidal type¹; Dalradian Quartzite (Pre-Cambrian), Kentallen, Argyllshire, with little microperthite, pyrite and a minimum of siliceous cement²; Appin Quartzite from same region, similar²; Hartshill Quartzite (Pre-Cambrian) of Warwickshire, a pinkish compact type with somewhat worn quartz grains, a little feldspar, chloritic matter and epidote after ferromagnesian minerals, also siliceous

cement, in many cases recrystallized about detrital grains³; Stiper-stones Quartzite (Ordovician), Shropshire, with mica and silty siliceous cement⁴; Estuarine quartzites, Commondale, Glaisdale, Castle-ton, etc., Yorkshire, compact types with cryptocrystalline groundmass⁵. See also under 'Ganister' (A2.5) below.

References

¹ H. H. Thomas, *Mem. Geol. Surv., Spec. Rep. Min. Resources Great Britain*, 16, 1920, p. 13.

² Author's observations.

³ W. W. Watts, *Summ. of Progress Geol. Surv. Great Britain*, 1897, p. 68, and *Proc. Geol. Assoc.*, 15, 1898, pp. 393, 397.

⁴ A. Harker, *Petrology for Students* (University Press, Cambridge), 1954, pp. 201, 206.

⁵ H. H. Thomas, *loc. cit.*, p. 13, pl. 2, Fig. 3.

General Reference

W. J. Sollas, *Sci. Proc. Roy. Dublin Soc.*, 7, 1892, p. 169.

(A2.5) GANISTER

[Pl. 46E, between pp. 208–209]

Def. A hard, compact, highly siliceous sedimentary rock, with fine, uniform, granular texture and composed essentially of angular quartz grains cemented with secondary silica.

Lith. In its strict interpretation ganister is a particular kind of highly siliceous rock, a variety of quartzite, comparable with the 'Sheffield Ganister', a well-known refractory material occurring in the Ganister group of the Lower Coal Measures. There are many varieties, from the pure quartzose rock to the less pure 'bastard ganister' and 'silica rock'. Ganister is hard, compact, uniform in texture, and of a blue-grey, buff or white in colour, often streaked with carbonaceous rootlets. Bedding seldom observed on a small scale. Fracture is characteristic, yielding smooth, subconchoidal hollows; newly broken edges very sharp. Some types have the appearance of 'hornstone'. Dark coloured types usually denote considerable impurity and are seldom true ganisters.

'In its typical form ganister is distinguished from flint and chert by its more granular texture and by the relatively small quantity of chalcedonic or amorphous silica'. . . . 'Bastard ganister' has been applied to a group of silica rocks which present many of the superficial characters of the true ganister, such as colour and the impressions of rootlets, but differ in certain essential details, namely in the increased amount of interstitial matter, the greater variability of texture, and often in a relatively incomplete silicification. It has become a practice to call other sandstones and quartzites which are capable of employment for silica brickmaking "silica rock" to distinguish them from true ganisters'. (See *General Ref.* H. H. Thomas.)

Text. Homogeneous, compact, fine-grained; sometimes granular or saccharoidal.

Shape. SA.

Min. Comp. Al. Quartz, chert, orthoclase, feldspar and stable accessory minerals, e.g. iron-ores, tourmaline, rutile, anatase, titanite, zircon.

Au. Silica, hematite, limonite, kaolinite, sericitic mica, clayey matter.

Mech. Comp. Average grade-size 0.05 mm–0.15 mm. Coarser types up to 0.5 mm. Sometimes very small interstitial grains 0.02 mm. observed. Extremely coarse types show passage into normal grits.

Micro. Normal rock consists of a mosaic of angular quartz grains often remarkably uniform in shape and size. These may be closely packed, giving rise to an interlocking structure, or siliceous cement may be conspicuous in places. This cement is usually cryptocrystalline, often chalcedonic. Where grains vary in size, the smaller pack together between the larger. Finely divided carbonaceous dust frequently permeates the rock. A network of veins usually traverses the rock, filled with silica, limonite, carbon, rarely with calcite.

Types. Lower Coal Measures. Sheffield Ganister ('Hard Mine'), the type rock; another variety from Deepcar is saccharoidal and streaked with carbonaceous matter¹; another from Huddersfield contains abundant mica and rutile; the Hawksworth Ganister ('Guiseley Rock') is a very pure type²; Lower Coal Measures, ganister, of Wingfield Park, Ambergate; also Wessington area, Derbyshire³.

References

¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources Great Britain*, 6, 1918, p. 23.

² *loc. cit.*, p. 32.

³ Author's observations.

General References

For general account of ganister, silica rocks, etc., see H. H. Thomas, *Mem. Geol. Surv., Spec. Rep. Min. Resources Great Britain*, 6, 1918, and 16, 1920.

W. Davies, British resources of ganister and silica rock, *Trans. Brit. Ceram. Soc.*, 47, 1948, p. 53.

(A2.6) GREYWACKE (GRAUWACKE, GRAYWACKE)

[Pl. 46F, between pp. 208–209]

Def. 'A sandstone composed of 33 or more per cent. of easily destroyed minerals and rock fragments derived by rapid disintegration of basic igneous rocks, slates and dark coloured rocks. It may or may not be intensely indurated or metamorphosed' (V. T. Allen).

Lith. An old field-term which has been usefully revived to designate arenaceous rocks of a peculiar type, specially developed in British palaeozoic formations. Essentially a sandstone compounded of quartz and miscellaneous rock-particles of diverse origin, the latter often in excess of the detrital quartz. The very mixed character of these rocks is usually discernible at a glance, while the grey, green or darker colour is common. Often highly micaceous, well bedded, usually void of recognizable organic remains.

Text. Coarse to medium, 'gritty'.

Shape. A.

Min. Comp. Al. Rock-particles include fragments of basic rocks, slates, sandstones and volcanic lavas. Quartz, chert, quartzite, mica, iron-ores and usually scanty accessory minerals.

Au. Silica, ferruginous, chloritic and argillaceous matter.

Mech. Comp. Variable from sand-grade to much coarser material (rudaceous).

Micro. The microscopic study of these rocks is somewhat similar to that of breccias, only on a much smaller scale. The student has to be prepared for practically any rock-type in the form of small or large grains or flakes and a knowledge of the locality and geologic history of the rock under investigation helps considerably in determining the nature of the derived fragments present. Quartz presents no difficulties by itself, but the cementing material, being often packed full of fine rock-dust, is difficult of identification. Usually decomposition products such as mica, chloritic matter, kaolinite and/or epidote, are conspicuous. These rocks are for the most part structureless and exhibit a heterogeneous constitution of marked variation from one example to another.

Types. Ordovician 'greywacke' of Montgomeryshire, with abundant volcanic inclusions; Old Red Sandstone, Welsh Borders, purplish-grey, brown and greenish types with plutonic, volcanic and sedimentary rock-particles¹.

References

- ¹ G. W. Tyrrell, *Principles of Petrology* (Methuen, London), 1926, p. 209.

General References

- G. W. Tyrrell, Greenstones and Greywackes, *C.R. Réunion Inter. l'étude Pre-Cambrian, etc.*, *Bull. Geol. Cmttee. Finland*, **102**, 1933, p. 24.
G. Fischer, Die Petrographie der Grauwacken, *Jahr. Preussischen Geol. Landenstalt*, **54**, 1933, p. 320.
V. T. Allen, Terminology of Medium-grained Sediments, *Rep. Cmttee. Sedimentation, Nat. Research Council*, 1936, pp. 28, 46.

(A2.7) SILTSTONE

Def. A fine-grained arenaceous rock whose detrital particles are predominantly of the silt grade, *i.e.* 0.01–0.1 mm.

Lith. This type has been separated by J. F. N. Green* to comprise those rocks which are essentially compacted silts, conforming in grade to the latter raw material (Vol. I, Ch. IV, p. 179). They are principally products of fluvial, lacustrine, glacial and aeolian action, in other circumstances of volcanic origin and usually present distinctive features. The fine sandy character is typical, together with perfect lamination in the aqueous types. Such lamination may be picked out by different coloured iron-oxide films, depending on the degree of impregnation developed from plane to plane. Fine current-bedding and ripple-marking are also observed in some types. Organic remains

* See Reference ¹, p. 225.

are common, especially carbonaceous plant-fragments. Colour normally grey, buff or brown except in the aeolian types, when hematite staining may be prominent. Siltstones frequently illustrate the phenomenon of rhythmic banding, especially those of lacustrine origin.

Text. Essentially fine textured, close grained and compact; some varieties earthy.

Shape. SA in all except aeolian types, the latter SA to R.

Min. Comp. Al. Quartz, muscovite, feldspar, iron-ores and miscellaneous accessory minerals. Siltstones as a rule yield a fair quantity of heavy residue.

Au. Siliceous, ferruginous and calcareous cement; carbonaceous dust often present. Much of the irresolvable matter is clay.

Mech. Comp. Particles fall between the size-limits 0.01 mm. and 0.1 mm. Average about 0.06 mm.

Micro. In finely laminated varieties study by means of sections cut both parallel and transverse to lamination. The former exhibits a mass of fine quartz particles with cementing matter enveloping each, or clustered aggregates giving a patchy mosaic structure; this type of section should also show the relationship of the matrix to the detrital particles, the character of any organisms present and especially the development of mica. The transverse section exhibits some degree of parallelism of the component minerals, variations in these from plane to plane and longitudinal sections of any organisms present, *i.e.* those reposing normally with the bedding. In many examples the manner of impregnation of the authigenic matter is best studied from these transverse sections. Much of the cement, if argillaceous, may be difficult to decipher and may also prove optically inert, owing to its extreme finely divided state (see A3, below). Miscellaneous rock-particles, composite or simple in character, prevail in some examples, thus allying the type with the 'greywackes' (A2.6, p. 223). The presence of calcite is frequent and is usually easily detected.

Types. Silurian of North Wales; also Lake District¹; Old Red Sandstone, Caithness, N.B., slaty 'flagstones' with abundant lime and organic matter²; Keuper silts and marls, Leicestershire³; Ashdown Sand (Wealden), Sussex, siltstones of fluvatile origin, finely laminated, ferruginous cement, with plant remains, ostracods, etc.⁴; Weald Clay siltstone (Wealden), Horsham, Sussex, with calcareous cement, lignite, etc.⁵.

References

¹ J. F. N. Green, in A. Holmes, *Nomenclature of Petrology*, 2nd ed. (Murby, London), 1929; *Siltstone*, p. 21.

² *Mem. Geol. Surv. Scotland, Geology of Caithness*, 1914, p. 89.

^{3, 4, 5} Author's observations.

(A3) ARGILLACEOUS DEPOSITS. This division comprises all the finest mechanically-formed sediments, represented essentially by clays and those rock-types produced therefrom by consolidation and by expression of moisture. The constituent particles range from

an upper limit of 0.01 mm. in diameter to ultra-microscopic and colloidal matter. Of all sediments these have always proved the most difficult to investigate thoroughly from a petrological standpoint, owing to the finely divided state of their components and also because of the difficulty of determining by ordinary methods much of the authigenic matter which as 'clay paste' defies diagnosis by petrological means alone. The intensive use of improved optical, X-ray and base exchange studies of clay minerals has, however, provided a most valuable technique for investigating these finely divided materials; much that for long eluded interpretation has been clarified by research along these lines.

Recent work has shown that at all events kaolinite does not play the supreme part in constitution of these rocks as formerly imagined; only in certain restricted types is this mineral really prevalent. Much modern work on soils, also on clays employed in the ceramic industry, has thrown a flood of light on the real composition of argillaceous rocks and recognition of the nature and role of the 'colloidal complex', mostly attributable to various hydrated aluminous silicates, has proved a realistic approach towards their better understanding. In another direction, chemical and physical analyses of various clays suited to particular purposes in the arts, led to certain definite conclusions on mineralogical composition. The original work of C. S. Ross and E. V. Shannon on bentonite¹, for instance, was a distinct advance at the time and inspired much similar research on other types of clay, hence on the consolidated rocks to which it gives rise.

Several attempts were made in the past to bring the varied clay types within a comprehensive scheme of classification, especially in America; such classifications depended either upon origin, chemical analysis, physical properties or on their behaviour under conditions of heat or desiccation. As with attempts at mineralogical classification of clays, none succeeded in bringing within a convenient compass all varieties known, or in framing a logical scheme as a basis of petrological analysis and description. The different classifications enunciated by E. Orton², H. A. Wheeler³, G. E. Ladd⁴, E. R. Buckley⁵, G. P. Grimsley and F. F. Grout⁶, H. Ries⁷, and A. B. Searle⁸ reveal the somewhat chaotic conditions prevailing in clay technology in those days. Thus, although argillaceous rocks in general and clays in particular, now enjoy a literature far surpassing in bulk that available in connexion with any other sediments, descriptions are still often arbitrary, biassed according to the particular angle from which the writer happens to view the subject.

In recent years, however, a more orderly procedure and grasp of fundamentals has been achieved and our present knowledge of

clay mineralogy, so ably catalogued by G. W. Brindley and his associates in the Clay Minerals Group of the Mineralogical Society, London¹⁰; by R. E. Grim in his classic text-book¹¹; and by D. Carroll in this present volume¹², bears eloquent testimony to the enormous advances made in studies of these complex 'finer aggregates of mineral particles'.

The author has confined himself in this volume to those varieties of argillaceous rocks most commonly encountered in the course of geological investigations and no attempt is made to widen its province by inclusion of many special and localized types extant. For these the reader is referred to existing text-books devoted entirely to this subject^{9,10,11}. Thus restricted, the argillaceous group may be said to comprise the following principal types:

- (A3.1) Clay (p. 227).
- (A3.2) Fireclay (p. 231).
- (A3.3) Fuller's Earth (p. 232).
- (A3.4) Aeolian Clay (p. 233).
- (A3.5) Abyssal Clay (p. 234).
- (A3.6) Volcanic Clay (p. 236).
- (A3.7) Residual Clay (p. 237).
- (A3.8) Mudstone (p. 239).
- (A3.9) Shale (p. 240).

¹ *Journ. Amer. Ceramic Soc.*, **9**, 1926, p. 77.

² *Ohio Geol. Surv.*, **7**, p. 52.

³ *Missouri Geol. Surv.*, **11**, 1897, p. 25.

⁴ *Geol. Surv. Georgia, Bull.* **6a**, 1898, p. 12.

⁵ *Wisconsin Geol. Surv., Bull.* **7**, pt. 1, p. 14.

⁶ *W. Virginia Geol. Surv.*, **3**, 1906, p. 70.

⁷ *Clays, Occurrence, Properties and Uses*, 2nd ed. (Chapman and Hall, London), 1914.

⁸ *Natural History of Clay* (C. Griffen, London), 1912, p. 165.

⁹ H. Ries, *op. cit.*

¹⁰ *X-ray Identification and Crystal Structures of Clay Minerals*, 1951.

¹¹ *Clay Mineralogy* (McGraw-Hill, New York), 1953.

¹² Ch. III, p. 288.

(A3.1) CLAY*

[Pl. 47A, between pp. 208-209]

Def. Clay is essentially a physical state of finely divided mineral matter in which individual diameters of constituent particles range from 0.01 mm. down to colloidal dimensions and in which hydrated aluminous silicates enter chiefly in composition.

Lith. The distinguishing visual feature of true clay is its plasticity when

* See also Ch. III, this volume.

wet, due to adsorbed moisture by the extremely fine mineral particles of which it is composed. Expulsion of that moisture, whether by natural or artificial means, brings about a change of state and the rock passes into a mudstone (A3.8) or, with the development of lamination, into a shale (A3.9). Beyond the feel of this rock, recognition of its plastic properties and colour, little is usually discernible from megascopic examination unless organic remains are present, which is a variable feature, depending on stratigraphical horizon. Colour is generally significant. *White* implies absence of iron compounds, carbon or manganese, such clay being essentially composed of hydrated aluminous silicates. *Yellow* suggests incipient oxidation of iron compounds, more rarely chrome ochre. *Brown* clay shows evidence of ferric oxide passing into limonite. *Red* is chiefly due to the presence of ferric oxide (hematite) in finely divided state. *Mauve* colouring suggests manganese dioxide, limonite and sometimes a trace of cobalt compounds. *Purple* is usually due to hydrated manganese dioxide with limonite. *Green* colour may be partly due to finely disseminated chloritic or glauconitic matter, in some cases to the presence of ferrous silicate and ferrous sulphate. *Grey* is inferential of the white type plus admixture of finely divided carbonaceous matter (graphite, carbonized wood, plant fibres, etc.). *Black* clay is usually due to an excess of carbonaceous matter, as above, or it may be due to bituminous impregnation; in deoxygenated environments the black colour may be accounted for by amorphous ferrous sulphide, less commonly by black oxide of manganese. The significance of colour as inferential of sedimentary environment is discussed on p. 450. Many examples exhibit blended colouring (variegation)*. Clays with pebbles, flints, boulders, etc., are composite types, the products of particular and local conditions, e.g. glacial boulder clay, clay with flints; in these instances studies of the large components and of the clay-matrix should proceed separately.

Text. Exceedingly fine.

Shape. A to SA.

Min. Comp. *Al.* Quartz, orthoclase or soda-plagioclase feldspars, primary muscovite, biotite, ilmenite, epidote (in part), tourmaline, zircon, rutile, titanite; less commonly hornblende, garnet. Other accessory minerals are rare.

Au. Hydrated aluminous and/or magnesium silicates, silica, hydroxide and carbonate of iron, muscovite, calcite, chloritic matter, epidote, glauconite, carbonaceous matter, secondary rutile and anatase. Among the hydrated aluminous and/or magnesium silicates, the following have been specifically determined and are significant in modern clay mineral classification†: allophane, chlorite group, dickite, halloysite, hectorite, 'illite' group, kaolinite, montmorillonite, nacrite, nontronite, saponite, sauconite, sepiolite and vermiculite. In special types the hydrated aluminium oxides bauxite, diasporite and gibbsite are important constituents.

* H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 313.

† See A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Resources Great Britain*, 29, 1925, p. 33. also *General References*, p. 230.

(*Note*.—Most of the above species are separately described in Ch. I, this volume.)

Mech. Comp. Grade-size of the detrital particles is < 0.01 mm. In many examples the diameters are considerably less; below 0.005 mm. it is extremely difficult to promote deflocculation and secure isolation of particles. Below 0.002 mm. particles are practically in colloidal suspension. Ordinary microscopical observations impracticable on particles of diameters less than about 0.002 mm.

Micro. The difficulty of making a thorough microscopical study of clays from the petrological standpoint has already been emphasized. Where thin sections are available much depends on the skill with which they have been cut, largely a question of the amount of desiccation and loss of plasticity which has been achieved in preparation of the material. The dried, gently powdered clay forms for the most part the most profitable material to work upon, suitable segregations being made by centrifuging, heavy liquids, etc. Much may be learnt about ordinary clays, however, if attention is paid to the following points. Study first the obvious detrital constituents revealed in the prepared concentrates; if these present difficulty on account of extreme fineness proceed by the special technique described for fine material, Vol. I, Ch. III, p. 124, and segregate in the usual way for loose detrital sediments. Quartz is usually in subangular flakes, seldom clear, but turbid with argillaceous matter; check with polarized light. Felspar, if present, is revealed by twin lamellae in polarized light, *using high power objective*, incidentally essential in all work on clays. Mica is normally of the sericitic type and shows up in the form of silky wisps or flakes of characteristic birefringence and refractive index. Spherulitic siderite may occur in certain varieties. Iron-ores and carbonaceous specks are best displayed by employing strong incident light; this also is of great help in differentiating the aluminous silicates or 'clay paste' background in which the detrital particles are set. In thin section polarized light will indicate approximately relative proportions of allogenic to authigenic matter, since quartz is nearly always the most prevalent detrital mineral and is quickly revealed by characteristic interference (usually yellow colours in clay sections owing to the difficulty of producing them to standard thickness); the 'clay paste' itself is normally observed to be structureless until high power magnification coupled with reflected light observations are made; then is revealed an organized development of crystalline aggregates, often coloured, sometimes opaque, sprinkled with minute dust particles, probably iron-ores, carbonaceous specks, possibly rutile; such aggregates include one or more of the above-mentioned hydrated aluminous and/or magnesium silicate minerals, to be identified in a majority of cases only by exhaustive X-ray, spectroscopic, chemical and optical tests. When kaolinite occurs, it varies in form from tabular, pseudo-hexagonal plates to fan-like sheaves, vermiform or 'rouleaux' assemblages of minute crystals¹; note refractive index and interference colours and compare with quartz; if the stage is rotated, using polarized light, kaolinite in thin section

is observed to extinguish more tardily than quartz²; fibrous forms exhibit extinction angles from 15° to 20°; basal cleavage flakes (common occurrence), if not too small, yield biaxial figure. Much of the white, amorphous, powdery or 'unglazed porcelain' looking material may be halloysite, quite inert to polarized light; but any particularly abundant, but undeciphered, constituent, should be isolated and fully investigated *per se* to fix its identity.

Types. Fairlight Clay (Wealden), Fairlight, Sussex, variegated clays with spherulitic siderite, lignite and plant remains^{3,4}; Gault (Upper Cretaceous), grey clay with glauconite, pyrite and *foraminifera*⁵; Reading Beds (Eocene), West Kent, Surrey etc., mottled clays with plant remains⁶; London Clay (Eocene), Harefield, Middlesex and elsewhere, bluish-grey clay with pyrite, selenite, calcite, etc.⁷; Upper Oligocene lignitic, white and brown clays of Bovey Tracey, Devonshire⁸; Pliocene, St. Agnes, Cornwall, brown clay with good detrital constituents⁹; Glacial Boulder Clay (Cromer Till, etc.) of East Anglia, grey unstratified boulder clay with shell-fragments and pebbles of rocks of British and Scandinavian origin etc.^{10,11}.

References

- ¹ J. A. Howse, *Handbk. to Coll. Kaolin, etc., Mus. Pract. Geol.*, London, 1914, ch. vi, p. 145.
- ² R. E. Somers, *U.S. Geol. Surv., Bull.* 708, 1922, p. 296.
- ³ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 312; also
- ⁴ E. Spencer, *Quart. Journ. Geol. Soc.*, 81, 1925, p. 667.
- ⁵⁻¹⁰ Author's observations.
- ¹¹ A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, p. 627.

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- R. E. Grim, *Clay Mineralogy* (McGraw-Hill, New York), 1953.
- Note.*—See also bibliography in Ch. III, this volume.

(A3.2) FIRECLAY*

 [Pl. 47B, C, *between pp. 208–209*]

Def. A form of siliceous clay often forming 'seat-earth' to coal seams and used for refractory purposes, capable of withstanding high temperature firing without disintegrating or melting.

Lith. The typical Coal Measure fireclay of the Midlands is a highly siliceous clay, low in alkali and lime content, in some varieties coarse enough for quartz particles to give a 'gritty' character to the rock; such approximate petrologically the siltstones (A2.7) or 'grey-wackes' (A2.8). Generally, however, fireclay is a compact, homogeneous, consolidated clay, with or without lamination. Colour varies from slate-grey to brown or brownish-black, some types possessing a mauve tint. Carbonaceous remains common, sometimes recognizable plant-fragments, more often occurring just as streaks or clots. Coarse varieties have the most detrital material, the finer varieties resembling shale in lithologic character and composition. Types with small silica content are often earthy.

Text. Exceedingly fine; sometimes 'soapy'; earthy.

Shape. A to SA.

Min. Comp. Al. Quartz, felspar, muscovite, biotite, occasionally rock-particles, iron-ores and varied accessory minerals. Many examples yield plentiful 'heavy' residues.

Au. Mica, chloritic matter and minerals of predominantly micaceous habit (hydrated aluminous silicates), epidote, secondary silica and iron compounds, occasionally calcite and commonly rutile ('clay-slate needles'). These constituents, some or all, form the 'clay-paste' especially characteristic of these rocks and for the most part difficult to analyse mineralogically.

Mech. Comp. Average grade 0.01 mm., but detrital quartz often of the silt grade, 0.05 mm. Clay-matter often extremely difficult to break down into individual particles.

Micro. The chief feature of fireclay is the abundance of free quartz in the form of small, equi-dimensional grains of granular habit. In a few varieties these grains are so plentiful as to constitute the rock a siltstone in the strict petrological sense; generally, however, the dark brown matrix is very prominent. Felspar is occasionally diagnosed, but more often is probably represented by decomposition products. The paste includes minute scales of secondary mica, various hydrated aluminous silicates (as for clay, p. 228), iron-ore dust (probably ilmenite) and obvious rutile needles. This form of rutile differs considerably from the primary detrital type; it occurs in slender, acicular crystals, often of perfect formation, almost colourless and with extremely high refractive index; twin forms also observed; J. J. H. Teall recorded needles of rutile of this type 0.001 mm. in thickness,

* Commercial 'fireclay' includes a number of differently formed clays and allied rocks suited to various refractory purposes. The term is here restricted to highly siliceous, transported clays of the Coal Measure type, distinct from miscellaneous residual clays, which receive separate consideration in accordance with their undoubted difference in origin and constitution.

averaging 0.002 mm., their length being from 8 to 30 times their breadth¹. Usually where lamination is developed, there is a certain degree of parallelism in the orientation of the detrital elements in the matrix, also discernible in the fibrous minerals of the latter. Where no bedding occurs, the larger grains are distributed haphazardly through the 'paste' and the rock is practically devoid of any distinctive micro-structure.

Types. Coal Measure fireclays of Newcastle-on-Tyne, etc., Northumberland, coarse and fine laminated varieties²; Middle Coal Measure fireclays of Stockingford, Nuneaton, Warwickshire; Coal Measure clays of Leeds, Halifax and Huddersfield, Yorkshire, typical siliceous clays with carbonaceous matter, micaceous minerals, rutile and other accessories; Millstone Grit, Glenboig Fireclay, Central Valley, Scotland^{3,4}.

References

¹ *Miner. Mag.*, 7, 1887, p. 201.

² W. M. Hutchings, *Geol. Mag.*, 1890, pp. 264, 316; 1891, pp. 164, 304; 1894, pp. 34, 64; 1896, pp. 309, 346.

³ J. W. Gregory, *Proc. Roy. Soc. Edinburgh*, 30, 1910, p. 348.

⁴ J. S. Flett, *Geology of Glasgow District*, *Mem. Geol. Surv. Great Britain*, 1911, p. 219.

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A. H. Cox, *Geol. Mag.*, 1918, p. 56.

See also *Mem. Geol. Surv. Great Britain Refractory Materials*, 28, 1924, p. 3.

(A3.3) FULLER'S EARTH

[Pl. 47D, between pp. 208–209]

Def. Fuller's Earth is the name given to a particular form of clay composed substantially of montmorillonite, plus anorthoclase feldspar (containing lime), the whole possessing low plasticity and strong decolorizing and degreasing properties.

Lith. A soft, earthy rock, of distinctive texture, colour and physical properties. Bedding may or may not be developed. Colour greenish-brown, grey, bluish-grey or yellow. Possesses marked absorbent properties. When scratched with the finger-nail, yields a polished streak. Adheres to the tongue. Crumbles in water and cannot be 'mudded'.

Text. Very fine, close-grained, powdery or earthy; distinct 'clayey' feel.

Shape. SA.

Min. Comp. Al. Quartz, mica, glauconite, calcite; accessory minerals include iron-ores, zircon, apatite, fluorite, locally barite, sphalerite, titanite, gatenite, hornblende, biotite¹.

Au. Hydrated silicate of aluminium, which makes up the bulk of the rock. 'Fuller's earth material', together with anorthoclase feldspar, contains lime.

Mech. Comp. Average grade-size < 0.005 mm.

Micro. Difficult to study in thin section. Refractive index, X-ray and chemical methods essential to complete investigation. Usually an abundant and distinctive mineral suite can be separated in the ordinary way. Plant remains and micro-organisms observed. Practically structureless; essentially an aggregate of aluminous silicate particles plus varying amount of detrital constituents.

Types. Fuller's Earth (Bathonian), W. of England^{2,3}; Fuller's Earth (Lower Cretaceous), Redhill, Nutfield, etc., Surrey, with interesting accessory mineral assemblage^{1,3}.

References

¹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, pp. 63, 92, 93.

² A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, pp. 415, 422, 424, 425.

³ E. F. Newton, *Proc. Geol. Assoc.*, 48, 1937, p. 175.

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M. N. Broughton, Texas Fuller's Earths, *Journ. Sed. Pet.*, 1932, p. 135.

E. F. Newton, *loc. cit.*, p. 197.

(A3.4) AEOLIAN CLAY

[Fig. 46]

This subdivision is exemplified by the Eurasian Loess and American Adobe, both partly of aeolian and partly of fluvio-glacial origin.

Def. Loess is commonly a yellow, porous silt, clay or marl composed of finely divided mineral matter (? glacial) deposited by wind action. Adobe is a loess-like deposit consisting of fine grained, porous silt and marl deposited in arid desert basins of Western and Central America.

Lith. Yellow, buff, grey or brown calcareous clay, often somewhat silty. Very slightly coherent and easily powdered in the fingers, yet possessing remarkably resistant properties to subaerial erosion. Plant remains in various stages of preservation scattered throughout the rock.

Text. Fine, compact, earthy.

Shape. A.

Min. Comp. Al. Quartz, orthoclase, plagioclase, muscovite, biotite, magnetite, amphibole, pyroxene, etc.

Au. Calcite, dolomite, silica, clay material, carbonaceous matter.

Mech. Comp. Average grade < 0.0025 mm. 'Out of 150,000 particles examined under the microscope only about 3% measure above .0025 of a millimetre and 1% over .005 of a millimetre' (loess)¹; with adobe the upper limit is about 0.08 mm.

Micro. The constituent particles of this type of deposit are normally very fresh and transparent; their unassorted size and markedly angular shapes are characteristic. When cohesive, the calcareous nature of the cementing medium is seldom in doubt. Vegetable remains prevalent. Practically no organized micro-structure. Microscopical examination confirms the entirely haphazard nature of these deposits.

Types. Loess of China²; Russia, Germany (Rhine Valley) etc.; similar deposits of the Mississippi Valley, U.S.A.³; adobe of South California, Colorado, Wyoming, etc.⁴.

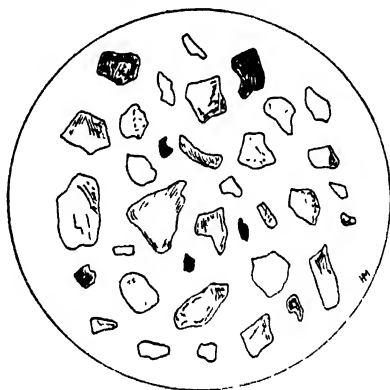


FIG. 46. Grains from the Loess, China. (After G. P. Merrill)
[$\times 25$.]

References

¹ G. P. Merrill, *Rocks, Rock-Weathering and Soils* (Macmillan, London), 1913, p. 315; also E. V. Emerson, *Journ. Geol.*, **26**, 1918, p. 532.

² F. von Richthofen, *China*, vol. i, 1877; also R. Pumpelly, *Amer. Journ. Sci.*, **17**, 1879, p. 133.

³ C. R. Keyes, *Amer. Journ. Sci.*, **6**, 1898, p. 299.

⁴ I. C. Russell, *Geol. Mag.*, **26**, 1889, pp. 242, 289.

General Reference

H. Klähn, *Sedimentation subaerischer Sedimente (Sand und Löss)*, *Zeit. Deutsch. Geol. Gesell.*, **85**, 1935, p. 35.

(A3.5) ABYSSAL CLAY

Lith. This subdivision includes varied muds and clays laid down at the greatest depths of the oceans. These rocks are in general very finely divided and are studied as aggregates of incoherent particles from samples dredged from sea-bottom. In certain cases a latent degree of coherency results in solidification to mudstone or shale. Varieties are chiefly distinguished by colour, though there are striking differences in mineral composition revealed by microscopical observations. *Red Mud* owes its colour to ferric oxide. *Red Clay* (so-called) varies from yellowish-red to purple, depending on the ferric oxide and

manganese peroxide contents. *Blue* and *Grey Muds* are coloured chiefly by ferrous sulphide plus organic matter, the latter especially characteristic of *Black Muds*; *Green Mud* is largely due to the presence of glauconite.

Text. Extremely fine, soft, often greasy.

Shape. A.

Min. Comp. Al. Quartz, iron-ores, tourmaline, zircon, garnet; where volcanic rocks have contributed, augite, olivine, hypersthene, hornblende, plagioclase, sanidine, etc.

Au. Silica, calcite, glauconite, lime phosphate, argillaceous matter.

Mech. Comp. Variable, down to 0.005 mm., but may contain particles of much larger size; some of the 'muds' average 0.12 mm.

Micro. Usually a sharp contrast is shown between the organic and inorganic ingredients of these deposits. In the *Red Muds*, quartz and the common terrigenous minerals (above) are associated with diatom frustules, sponge spicules and rarely radiolarian tests. *Red Clay* contains (in order of abundance) magnetite, manganese dioxide, felspar, glassy volcanic particles, augite, pumice, hornblende, pelagonite, quartz, plagioclase, mica, phillipsite or zeolitic matter, cosmic spherules, sanidine, scoriae, glauconite, olivine, lapilli, rock-fragments, zircon, tourmaline, epidote, garnet. Organic remains include shark teeth, diatoms, *radiolaria*, *foraminifera*, etc. *Blue* and *Grey Muds* show quartz, orthoclase, plagioclase, green hornblende, augite, white and black mica, epidote, chloritic matter as flakes, zircon, tourmaline and miscellaneous rock-fragments; glauconite not common. Abundant siliceous and calcareous micro-organisms. The *Black Muds* show variable mineral composition, much quartz, carbonaceous matter, mica, etc., with pyrite as a conspicuous constituent; organic remains include planktonic diatoms and pelecypod fragments. *Green Mud* is distinguished by its glauconite, also by some doubtful substance of organic origin. Minerals include quartz, felspar, magnetite, hornblende, augite, tourmaline, zircon, garnet. In all these deposits, a contribution from submarine volcanic rocks or far-travelled volcanic dust - the product of violent eruption - determines the presence of ordinarily uncommon sedimentary rock minerals.

Types. Deep Sea deposits of the Challenger Expedition, Atlantic, Pacific, etc.¹

References

- ¹ J. Murray and A. F. Renard, *Deep Sea Deposits*, Challenger Report, 1891; also L. W. Collet, *Les Depots Marins*, 1908.

General References

- H. Scupin, Ist der Dictyonemashiefer eine Tiefseeablagerung, *Zeit. Deutsch. Geol. Gesell.*, 73, 1921, p. 153.
 R. Ruedemann, Faunal facies differences of the Utica and Lorraine Shales, *Bull.* 267, *New York State Mus.*, 1926.
 P. E. Raymond, The Significance of Red Colour in Sediments, *Amer. Journ. Sci.*, 13, 1927, p. 234.
 R. H. Rastall, The Petrography of the Hunstanton Red Rock, *Geol. Mag.*, 67, 1930, p. 436.

- H. Williams and O. M. B. Bulman, *The Geology of the Dolwyddelan Syncline (North Wales)*, *Quart. Journ. Geol. Soc.*, **87**, 1931, p. 425.
 W. H. Twenhofel, *A Treatise on Sedimentation*, 2nd ed. (Ballière, Tindall and Cox, London), 1932.
 H. Schmidt, *Die Bionomische Einteilung der Fossilien Meeresboden*, *Fort. der Geol. und Palaeontol.*, **12**, 1935.
 F. H. Hatch and R. H. Rastall, *The Petrology of the Sedimentary Rocks*, 3rd ed. rev. M. Black (Allen and Unwin, London), 1938.

(A3.6) VOLCANIC CLAY

Under this heading are placed certain distinctive clays of definite constitution and origin, *e.g.* *bentonite*, implying derivation from devitrified and chemically altered glassy, volcanic ash or tuff. The chief types have been described from America. Closely allied is the abyssal variety of volcanic mud (*q.v.* above).

Lith. Extremely variable in external appearance and superficial properties. Generally well stratified. Colour white, cream, dull green, sometimes blue or pink. Yellow to brown on weathering. Readily absorbs moisture, becoming plastic; excess of water causes formation of slime. Some samples exhibit sandy streaks or patches. Organic remains rare.

Text. Compact, soft; 'some have a very loose felt-like texture'¹.

Shape. A to SA.

Min. Comp. *Al.* Quartz, felspar, mica, ferromagnesian minerals, zircon, apatite, iron-ores.

Au. Montmorillonite, less commonly beidellite (in bentonite); non-bentonitic clays of similar origin may include halloysite and kaolinite. Abyssal volcanic mud is characterized by siliceous and calcareous matter.

Mech. Comp. Average grade 0.01 mm., but much of the material is of colloidal dimensions.

Micro. In the case of bentonite 'microscopic examination between crossed nicols . . . shows that the characteristic mineral of bentonite is crystalline. . . . In some specimens the material is very fine grained, but in most of them the crystal grains can be seen even with low power magnifications. The mineral has a micaceous habit, and moderately high birefringence perpendicular to the cleavage. The groups of plates that have been derived from single glass fragment commonly have a definite arrangement and sharply outline the original fragment. In most types of bentonite the crystal plates stand perpendicular to the original surface of the glass fragment, and the resulting crystalline area is now composed of two parallel rows of micaceous plates that often have a parting line between them. In other specimens the micaceous plates have developed parallel to the sides of the glass'¹. Generally the main constituent of these volcanic clays is montmorillonite together with some form of glass, the particles being essentially sections of 'bubble boundaries'. Detrital quartz tends to be restricted; feldspars and above-mentioned accessory minerals prevalent. These rocks vary in mineral composition, but all present interesting problems in microscopical analysis.

Types. Bentonite, Big Horn Basin, Wyoming, with andesine, orthoclase, biotite and accessory minerals, hydrated aluminous silicates (as above)²; also examples from Kansas, Texas, Oklahoma etc.¹, volcanic mud from deep sea deposits (Challenger Expedition)³; bentonite, Alberta, Canada, associated with coal, etc.⁴.

References

- ¹ C. S. Ross and E. V. Shannon, *Journ. Amer. Ceramic Soc.*, **9**, 1926, p. 77.
- ² D. F. Hewett, *Journ. Wash. Acad. Sci.*, **7**, 1917, p. 196.
- ³ J. Murray and A. F. Renard, *Deep Sea Deposits, Challenger Report*, 1891.
- ⁴ W. H. Twenhofel, *Treatise on Sedimentation* (Baillière, Tindall & Cox, London), 1932.

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- E. T. Wherry, Clay derived from volcanic dust in the Pierre of S. Dakota, *Journ. Wash. Acad. Sci.*, **7**, 1917, p. 576.
- C. S. Ross, Altered Palaeozoic Volcanic Materials and their Recognition, *Bull. Amer. Assoc. Pet. Geol.*, **12**, 1928, p. 143.
- C. S. Ross, H. D. Miser and L. W. Stephenson, Water-laid Volcanic Rocks of Early and Upper Cretaceous Age in South-Western Arkansas, South-Eastern Oklahoma and North-Eastern Texas, *U.S. Geol. Surv., Prof. Paper*, **154**, 1929.
- C. S. Ross and P. F. Kerr, The Clay Minerals and their Identity, *Journ. Sed. Pet.*, **1**, 1931, p. 62.
- P. F. Kerr, Bentonite from Ventura, California, *Econ. Geol.*, **26**, 1931, p. 153.

(A3.7) RESIDUAL CLAY

Lith. Residual clay, as the name implies, is any clay-material formed *in situ* from the decomposition of some particular rock, the minerals of which, by various destabilization processes, determine the nature of the ultimate clay-substance; in this respect, residual clay differs fundamentally from transported clay. The normal feature of residual clay is the extremely finely divided state of the clay-substance, though often the presence of fragments of miscellaneous rocks and minerals, more resistant to weathering than the parent-substances of the clay, determine an unsorted character. Some degree of plasticity is usually apparent when wet, but with expulsion of moisture, the clay hardens rapidly. Bedding normally absent, but a crude lamination of the solidified material is sometimes apparent. Organic matter not common, but where it occurs is mainly due to plant remains in varied stages of carbonization. Many residual clays are colourless or only slightly tinged with iron oxide staining; examples are the so-called 'pocket clay', formed in solution-cavities or pipes in limestone deposits, *bauxite*, *china clay* and *china clay rock*. The more intensely coloured varieties are illustrated by *laterite*, an exceedingly controversial substance which is reddish-brown or yellow.

Text. Exceedingly fine and uniform as far as the clay-substance is concerned; where rock-fragments or 'sand' are present, the texture becomes gritty, sometimes even coarse; laterite is variable, some examples being coarse, earthy and friable.

Shape. Clay particles A, less commonly SA. Most embedded rock-fragments are angular, like the components of a breccia. Loose quartz often corroded, therefore rounded.

Min. Comp. Rock-fragments may be of igneous or sedimentary origin; in 'pocket clay' they are less common, but include limestone, dolomitic limestone, occasionally basic igneous rocks; bauxite is, on the whole, remarkably free from large constituents, though fragments of basalt have been noted in one case; china clay and china stone (china clay rock) often include quartz-tourmaline rock (schorl), pegmatite, altered granite, cassiterite; laterite may comprise fragments of mother-rock, e.g. lava, basalt, granite, gneiss, also sandstone. The finer mineral components are quartz, hematite, limonite and varied accessory minerals; in china clay a distinctive assemblage of quartz, tourmaline, topaz, mica, cassiterite, fluorite, is characteristic. The clay-substance varies considerably; in pocket clay it is predominantly hydrated aluminous silicate, with kaolinite, halloysite, possibly montmorillonite, etc.; in bauxite it is essentially alumina and some form of ferric hydrate (goethite or limonite), as is the case with laterite; the alumina may be represented either by gibbsite or diaspore, though often the clay-substance gives the impression of being an amorphous mixture rather than individualized species.

Mech. Comp. Clay-material extremely fine, often colloidal. Gritty constituents usually conform to the medium sand-grade.

Micro. The 'floating' minerals or rock-fragments are the first components to attract attention and seldom present great difficulty in diagnosis. It is usual to find quite an arbitrary distribution of these constituents in the clay-mass, no particular relationship between the two being apparent. The clay-substance may or may not present a certain degree of micro-structure; in pocket clay it is reduced to a minimum unless much crystalline kaolinite is present, when the interlocking scaly plates of that mineral are discernible. Bauxite is frequently quite without structure, though in some examples a fibrous character (? gibbsite) with enveloping brown material (ferric oxide or hydrate) is conspicuous. In china clay, colourless, pseudo-hexagonal, scaly plates of kaolinite are associated with corroded quartz, white mica, topaz, etc., often in the form of interlocking crystal-masses set promiscuously in a very fine kaolinitic cement; the latter may include material having the properties of halloysite. Laterite presents considerable variation in micro-structure. Scales and fibres due to gibbsite may be observed, these often picked out by ferric hydrate staining; intimately mixed with this material are quartz particles, iron-ores, carbonaceous matter, etc. Diaspore has been recorded from some varieties of laterite, which in many respects closely resembles bauxite in micro-structure.

Types. 'Pocket clay' from the Carboniferous Limestone of Derbyshire, Staffordshire, etc.¹; bauxite deposits of Antrim²; china clay of West Cornwall^{3,4,5}; laterite of India⁶, Seychelle Islands⁷, French Guinea⁸, etc.

References

¹ Author's observations.

² The Intra-basaltic Rocks of N.E. Ireland, *Mem. Geol. Surv., Ireland*, 1912.

³ A. Howe, Handbook to the Collection of Kaolin, *Mus. Pract. Geol.*, 1914, p. 145.

⁴ *Mem. Geol. Surv.*, 347, 1909, ch. ix.

⁵ J. W. Gregory, *Elements of Economic Geology* (Methuen, London), 1928, ch. xiii.

⁶ T. H. Holland, *Geol. Mag.*, 1903, p. 59, and refs. cited.

⁷ M. Bauer, Beiträge zur Geol. der Setchellen, *Neues Jahr. für Min. etc.*, 2, 1898, p. 163.

⁸ L. L. Fermor, *Geol. Mag.*, 1915, pp. 28, 77, 123.

General References

T. V. M. Rao, A Study of Bauxite, *Miner. Mag.*, 21, 1928, p. 407.

C. S. Fox, *Bauxite and Aluminous Laterite* (Crosby, Lockwood, London), 1932; also *Geol. Mag.*, 69, 1932, p. 559.

(A3.8) MUDSTONE

[Pl. 47E, between pp. 208-209]

Def. An indurated non-laminated sediment composed of finely divided mineral matter of clay grade and composition.

Lith. Consolidation of clay without the production of fissile characters results in a type of rock to which, for want of a better name, the term 'mudstone' is applied; 'claystone' would suit equally well. The coarser varieties have affinities with 'siltstones' (p. 224). Chief lithological characters are colour, as variable as in clays, though usually dark green, brown or grey or a blend of these and an absence of anything but the crudest lamination. Organic remains, especially carbonaceous, very common. Oblique jointing and limonitic staining on planes thus developed are frequent features.

Text. Very fine; smooth surfaces.

Shape. A to SA.

Min. Comp. As for clay (*q.v.* p. 228).

Mech. Comp. Average particle dimensions < 0.01 mm. Much of the material is in a very fine state of division and is ultra-microscopic. (See relevant remarks under Clay, p. 229).

Micro. Although this rock-type lacks lamination, some degree of parallelism of orientation of constituent minerals is often discernible under the microscope, the result of compaction. Detrital matter together with organic remains if present is set in a fine clay-matrix in which certain components, *e.g.* silica, calcite, limonite, carbonaceous matter and one or more hydrated aluminous silicates, can be recognized. Predominant calcite or dolomite gives distinctive 'calcite' or 'dolomite mudstones'. With development of chamosite, siderite, etc., these rocks pass naturally into sedimentary ironstones (*q.v.* p. 279). Mudstones are sometimes traversed by veins of secondary silica or calcite carrying pyrite and related iron or copper ores. In certain types white mica, chloritic matter and secondary rutile are produced as a result of induration, such constituents forming a felted mass wrapping round quartz and the larger components.

Types. Graptolitic mudstones, Ordovician and Silurian, Welsh

Borders¹; Liassic mudstones (calcareous, pyrite and carbonaceous matter), Bridport, Dorset²; Wealden, Weald Clay mudstones, Sussex, Kent, etc.³.

References

^{1, 2, 3} Author's observations.

General References

J. J. H. Teall, *Miner. Mag.*, 7, 1887, pp. 201–204 (for rutile needles, etc.).
G. W. Tyrrell, *Principles of Petrology* (Methuen, London), 1926, p. 214.

(A3.9) SHALE

[Pl. 47F, between pp. 208–209]

Def. An indurated, laminated sediment composed of finely divided mineral matter of clay grade and composition.

Lith. Shale differs fundamentally from mudstone in its possession of definite laminations or bedding planes, parallel to which it splits with comparative ease. It represents, in fact, one stage further in consolidation of clay, mud, etc., than mudstone. Lamination may be thin or thick and is accordingly significant. Many fluviatile or lacustrine shales exhibit remarkably thin laminae, for instance, varve shales. Colour, as with clays (*q.v.* p. 228), frequently suggests conditions of deposition; grey, black or blue shales are usually derived from muds of marine, estuarine or fluviatile origin initially rich in carbonaceous and sulphide materials; these are the commonest types. Red shale owes its colour mainly to ferric oxide; green shale chiefly to chloritic material resulting from ferromagnesian mineral decomposition. Organic remains, both animal and vegetable, very prevalent; there is often an inherent relationship between nature and quantity of organisms and the colour of the shale: see ref. ¹, p. 241. Lignite seams and secondary pyrite common, especially in estuarine and fresh-water types; mineralized veins, *e.g.* calcite, quartz, barite, often developed; prominent jointing observed at right angles or obliquely to the laminae, or both.

Text. Fine, smooth; with inclusion of sand becomes gritty.

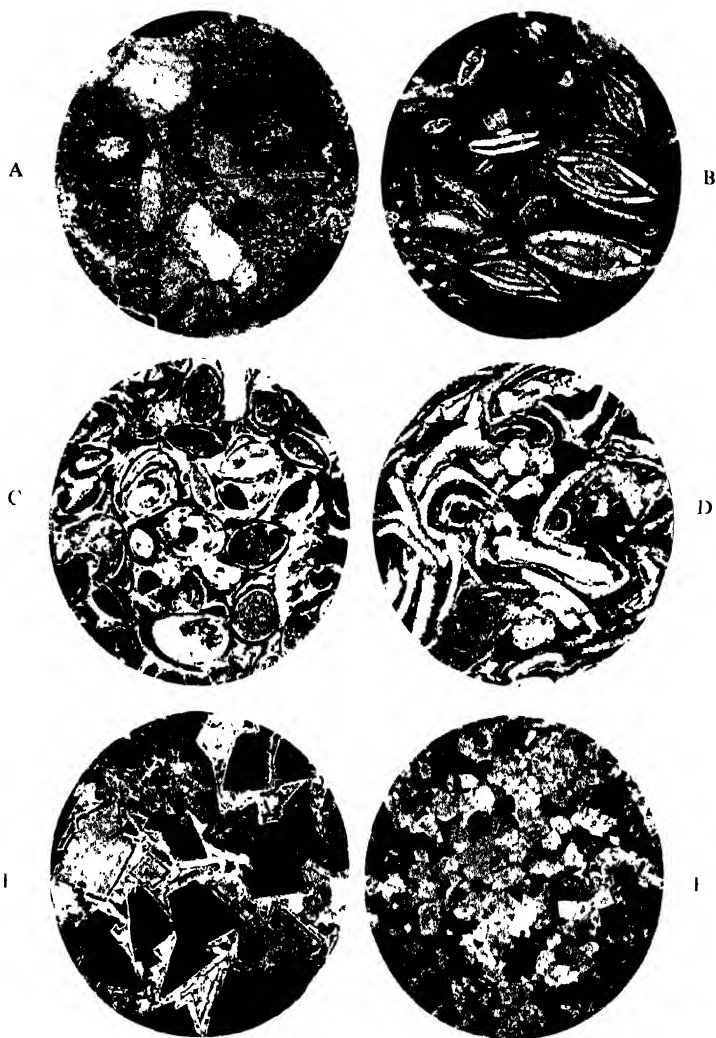
Shape. A to SA.

Min. Comp. Al. Quartz, mica, iron-ores and varied accessory minerals; occasionally feldspar.

Au. Secondary silica, calcite, limonite; usually abundant chloritic matter, amorphous carbon, rutile needles; less commonly titanite, leucoxene. Much of the 'background' of these rocks is indecipherable and represents products of induration of aluminous silicates such as are found in clays.

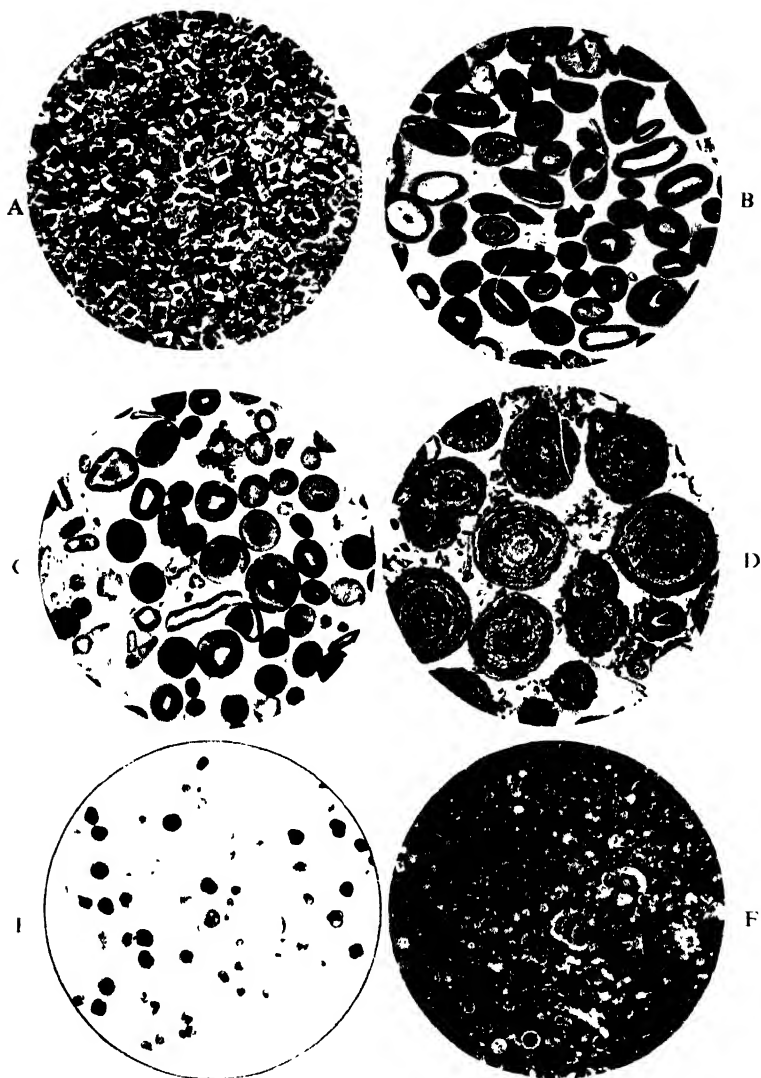
Mech. Comp. Detrital particles vary from silt to clay grade, usually, however, conforming to the former limits, 0.1–0.01 mm.; the finer particles are of true clay dimensions, frequently unmeasurable by ordinary means.

Micro. The dominant character of shale is the parallel orientation of its constituents, both organic and inorganic, revealed by thin section;



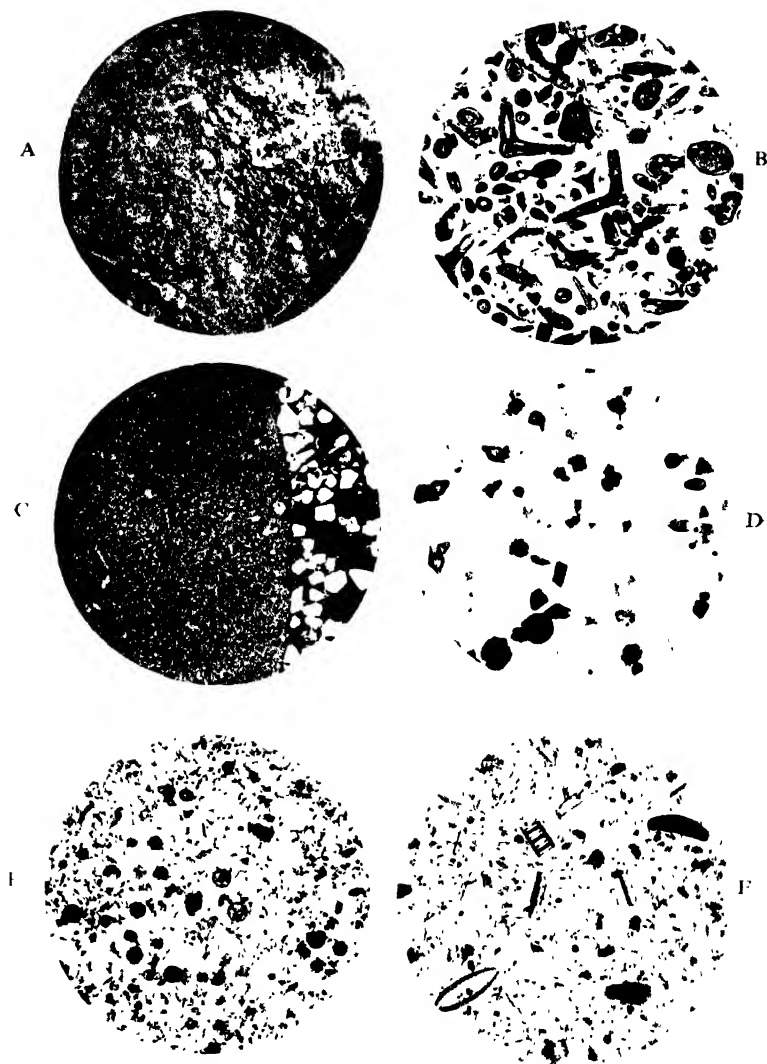
LIMESTONE AND DOLOMITIC LIMESTONE

- A Crinoidal Limestone (Carboniferous), Skrinkle, Bay, Pembroke [x 15]
- B Nummulitic Limestone (Eocene) Cairo, Egypt [x 15]
- C Ostracod Limestone (Purbeckian), Swanage, Dorset. [x 15.]
- D Shelly Limestone "Purbeck Marble" (Purbeckian), Purbeck, Dorset [x 15]
- E Dolomitic Limestone (Permian), Mansheld Woodhouse, Notty [x 15]
- F Dolomitic Limestone (Palaeozoic), Malew, I.O.M. [x 23]



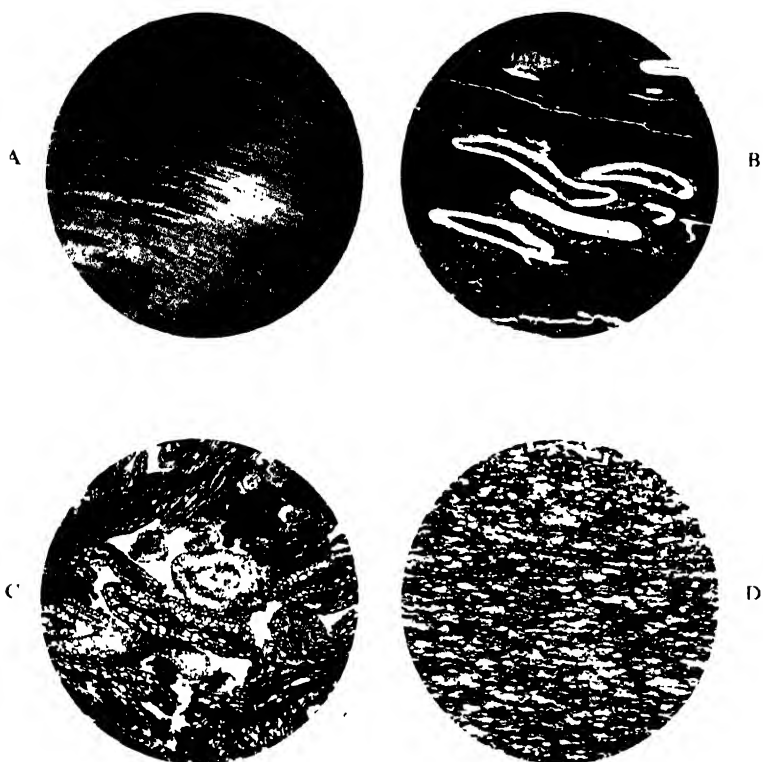
DOLOMITIC, OOLITIC AND PISOLITIC LIMESTONES, OOZE AND CHALK.

- A Dolomitic Limestone (Carboniferous), Burescombe, Somerset [x 42.]
- B Bath Oolite (Bathonian), Farley, nr. Bath [x 15].
- C Osmington Oolite (Corallian), Osmington, Dorset [x 20]
- D Pisolitic Limestone (Silurian), Malvern [x 9]
- E Globigerina Ooze, N. Atlantic Ocean, 1,260 fms [x 23.]
- F Chalk (Cretaceous), Laine, Antrim [x 35]



CHERT, FLINT, SILICIOUS OOZE AND DIATOMITE

- A Radiolarian Chert (Ordovician), Mulhous Is., Cornwall [x 23]
 - B Portland Chert (Portlandian), Swanage, Dorset [x 15]
 - C Flint, pebble in sandstone (Eocene), Hertfordshire "Pudding Stone" * [x 15]
 - D Radiolarian Ooze, S. Pacific, 2,425 fms. [x 25]
 - E Diatomaceous Ooze, Indian Ocean, 1,950 fms. [x 45]
 - F Diatomite, Loch Cuithir, Skye, N.B. [x 50]
- [*Crossed Nodules]



LIGNITE AND COAL

- A Lignite (Oligocene), Bovey Tracey, Devon [x 14]
 B Spore Coal (Coal Measures), Monra Colliery, Leicestershire [x 25]
 C Halifax Hard Coal (Lanarkian) Deighton, Yorks., with *Trigonopteris oldhami* [x 15]
 D Halifax Hard Coal (Lanarkian) Deighton, Yorks., with *Trigonopteris oldhami* [x 15]

such parallelism is best observed in sections cut transverse to the bedding, but the study should always be supplemented by sections cut parallel to the bedding. The latter show the mutual relationship of the constituents as they lie along one bedding-plane of the rock; in the case of organisms, *e.g.* plant spores, this amounts to a horizontal section; the relative proportion of detritus to shale-substance is also conspicuous in such horizontal sections. Transverse sections reveal the nature of the bedding, slight changes in constitution of material with alternating laminae and longitudinal or cross-sections both of minerals and organisms. Products of infiltrating solutions deposited along bedding-planes, in veins or cracks at right angles or obliquely to these, are also readily studied by such transverse sections. Usually the contrast between parallel and transverse sections is very marked. Shale-substance may be difficult to decipher, but the titanium minerals are normally conspicuous; much of the brown, translucent matter in many varieties is of carbonaceous origin and is frequently optically inert. Investigation by reflected light is often helpful, when limonite, aluminous silicate, secondary silica, green chloritic material, etc., may be clearly picked out in the mass. Muscovite, the ubiquitous shale mineral, presents characteristic features and is seldom difficult to diagnose. Accessory minerals must be studied from pulverized rock.

Types. Stockdale Shales (Silurian) of the Lake District, different coloured shales and their palaeontological significance¹; Upper Carboniferous shales, South Wales, with abundant rutile, etc.²; Culm Shale, N. Cornwall, with a silty form of carbon, etc.³; Lias shale, Dorset, Yorkshire, etc., with abundant organic remains, calcite, pyrite, jet; Kimmeridge Shale, Dorset; excellent example for study by horizontal and transverse sections⁵; Wadhurst Clay (shale developments) for ostracods, lignite and secondary minerals⁶.

References

- ¹ J. E. Marr, *Quart. Journ. Geol. Soc.*, **81**, 1925, p. 113.
- ² W. M. Hutchings, *Geol. Mag.*, 1896, p. 310.
- ³ C. A. McMahon, *Geol. Mag.*, 1890, p. 108.
- ^{4, 5, 6} Author's observations.

General References

- A. Brammall, *Miner. Mag.*, **19**, 1921, p. 211.
 W. W. Rubey, The Fine-Grained Upper Cretaceous Sedimentary Rocks of the Black Hills Region, *U.S. Geol. Surv., Prof. Paper* **165**, 1930.
 H. D. Hedberg, Gravitational Compaction of Clays and Shales, *Amer. Journ. Sci.*, **31**, 1936, p. 241.

(AB) CALCAREO-ARGILLACEOUS ROCKS. Transitional sediments partaking of certain prominent characteristics common both to argillaceous and calcareous rocks are sufficiently distinctive and widespread in development to warrant separate notice here. These are exemplified by the marls and calcareous shales. According to the scheme adopted they may be designated conveniently as follows:

(AB.1) Marl (p. 242).

(AB.2) Calcareous Shale (p. 243).

(AB₁) MARL

[Pl. 48A–C, between pp. 208–209]

Def. Marl denotes a calcareous clay devoid of consolidation and lamination and characterized by a certain degree of plasticity when moist.

Lith. The term marl is somewhat loosely applied to material having most of the normal attributes of clay, but also exhibiting considerable amounts of lime and/or magnesium carbonate. Usually a light coloured rock is implied, but this is not invariable, red, purple, chocolate and brown types occurring. Marls are usually homogeneous in superficial characters, often possessing plastic properties; with induration they pass into marlstone (calcareous mudstone), calcareous shale and argillaceous limestone, sometimes known as 'cement-stone' (p. 248). True marl, like clay, lacks obvious bedding and seldom exhibits any striking external structures, save those dependent on the presence of organic remains. Rudaceous constituents, pebbles, boulders, etc., may occur on a large scale. Some examples are gritty.

Text. Normally very fine, homogeneous, compact; plastic, 'soapy'.

Shape. A to SA.

Min. Comp. Al. As for clay (*q.v.* p. 228).

Au. As for clay, but with appreciable amount of calcareous matter disseminated in the clay-matrix; chemical analyses often show presence of magnesia, indicating magnesium carbonate. Anhydrite, gypsum, barite, celestite, are locally prevalent. Glauconite common in marine types.

Micro. Under the microscope marls present much the same features as clays; the detrital constituents are scattered haphazardly through a matrix in which much of the material is difficult, if not impossible, of diagnosis in terms of known minerals. Calcareous matter is generally betrayed by 'twinkling' on rotating the polarizer alone. Sulphates, if present, are often finely crystallized in fibrous aggregates of patchy occurrence. In coloured varieties the pigment is observed either as a staining material for the bulk of the rock or as irregular streaks traversing it. Where glauconite is in evidence, it frequently exhibits organic structure, *e.g. foraminifera*, and gives a distinctive appearance and colour to the rock. For the rest, the main mass of the rock is structureless unless the component minerals of the matrix can be made out, when a mosaic of equi-dimensional particles, often interrupted by dense interstitial matter, may be observed.

Types. Keuper Marls of Leicestershire, different coloured marls with gypsum, etc.¹; also of the Bristol district with variegated green, red and purple tints²; Chalk Marl of England, with glauconite, etc., and 'Chloritic Marl', Dorset, Isle of Wight etc.³; Oligocene (Bembridge) marls, Isle of Wight, white, red and blue marls with calcareous concretions and freshwater shells⁴.

References

- ¹ T. O. Bosworth, Keuper Marls around Charnwood, Leicester, *Leicester Lit. and Phil. Soc.*, 1912.
- ² Author's observations.
- ³ W. Hill, Cretaceous Rocks of Britain, *Mem. Geol. Surv.*, 2, 1903, ch. xxii.
- ⁴ J. W. Judd, *Quart. Journ. Geol. Soc.*, 36, 1880, p. 169, and E. Keeping, *Geol. Mag.*, 1887, p. 48.

General Reference

- C. A. Davis, A Contribution to the Natural History of Marl, *Journ. Geol.*, 8, 1900, p. 485; also A Second Contribution to the Natural History of Marl, *Journ. Geol.*, 9, 1901, p. 491; also Natural History of Marl, *Geol. Surv. Michigan*, 8, 1903.

(AB.2) CALCAREOUS SHALE

Def. An indurated, laminated sediment composed of finely divided mineral matter of clay grade and composition which also includes a substantial proportion of calcareous material. An indurated marl.

Lith. Shale in which occurs an appreciable quantity of lime is designated as calcareous shale, though no particular quantity has ever been specified; the term consequently has a wide and varied interpretation. It should be confined to indurated marl in which definite laminac have been produced as a result of compaction, a stage further in consolidation of marlstone. Argillaceous matter, however, is always in excess of calcareous in these rocks. Superficially there may be little to differentiate calcareous from ordinary shale, though the former is usually rather paler in colour than the latter, commonly grey, yellow, brownish-white. Lamination is often extremely fine; where the calcareous matter is concentrated in some layers more than others, alternating light and dark colour-banding may be manifest. Organic remains common.

Text. Very fine.

Shape. SA.

Min. Comp. Al. As for Shale (*q.v.* p. 240).

Au. Calcareous matter in addition to the normal shale minerals (*p.* 240), but often with much less rutile and limonite; silica is usually abundant and amorphous carbonaceous matter prevalent in dark coloured types.

Mech. Comp. The bulk of the material composing these rocks is very fine indeed, < 0.005 mm., the tendency to extremely fine particle dimensions increasing with amount of lime.

Micro. The presence of calcite in these rocks is revealed by the ordinary 'twinkling' with the polarizer alone. In some instances, however, chemical analysis may show the presence of lime in excess of that necessary to satisfy specific minerals and which might be anticipated in the form of a calcareous cement, yet no optical reaction can be discerned. As the rock passes more into the true limestone, calcite *per se* becomes prominent; argillaceous matter diminishes and the hybrid type 'argillaceous limestone' (*q.v.* p. 248) is produced; this

tends to exhibit certain characteristic microscopic features differentiating it from the type here under consideration. The study of calcareous shales should proceed as with ordinary shales, two sections being desirable, one parallel and one transverse to the laminae. If reaction for calcite is positive, note particularly the strength and nature of development of this material, what relationship it bears to included organisms (if any), to detrital quartz and to associated authigenic matter.

Types. Silurian (Woolhope) calcareous shale, Shropshire (Coalbrookdale, etc.)¹; Devonian Calceola Shales, South Devonshire²; Lias, Bridport, Dorset, calcareous shale in which the cementing matter can be well studied³; Oxfordian, Weymouth, Dorset, with free calcite, pyrite, plant remains and fine laminations⁴; Lower and Middle Purbeck, Dorset, calcareous shales with abundant organic remains, very fine laminae, plant remains⁵; Wadhurst Clay (Wealden) shales, with lignite, pyrite, fine laminae and colour-banding⁶.

References

¹ A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, p. 165.

² W. E. Ussher, *Quart. Journ. Geol. Soc.*, **46**, 1890, p. 499.

^{3, 4, 5, 6} Author's observations.

(B) ORGANIC ORIGIN

In this category are placed all those sediments owing their origin essentially to accumulation of organic matter of diversified nature. In contrast to rocks of mechanical origin which, as now explained, imply transport of constituents in a majority of cases, rocks of organic origin are for the most part formed *in situ*; they represent accumulations of the harder parts or more stable components of both animal and vegetable matter in environments and under conditions differing considerably from those normal to detrital sediments. These fundamental differences of origin are amply reflected by the rocks themselves, both in composition and micro-structure. The purest types are composed entirely of organic matter, but these are comparatively scarce in nature; usually a small but appreciable amount of mechanically-born sediment is apparent to emphasize the influence, even at a distance, of terrigenous material; with increase in proportion of detrital constituents, less pure types are evolved and gradually the gap is bridged between the two primary divisions of sedimentary rocks, *i.e.* of mechanical and organic origins (Groups A and B). Further, these organically-formed rocks are inherently susceptible to alteration both during and subsequent to consolidation by chemical reactions set up as a result of access of various substances in solution (metasomatism). Such changes are, when widespread and comprehensive, productive of types closely related to sediments fundamentally of inorganic chemical origin (Group C).

Intensive petrographic study of these rocks implies a working knowledge of the essentials of palaeontology and, to a lesser extent, of palaeobotany, since three main features come under observation in all cases: the organic remains, the matrix or cement (which may be of biochemical or simply of inorganic origin) and the inherent structure, *i.e.* relationship of organic constituents to matrix. To this must be added, in appropriate instances, the determination of foreign, mostly detrital, occasionally submarine volcanic or other igneous matter. Where marked changes in chemical composition are involved, a knowledge of theoretical interactions between the fundamental minerals, salts in solution or reactive substances in aqueous suspension helps considerably in the interpretation of the phenomena displayed.

For present purposes, rocks in this category may be subdivided into five groups on the basis of characteristic biochemical composition:

- (B1) CALCAREOUS (p. 245).
- (B2) SILICEOUS (p. 255).
- (B3) FERRUGINOUS (p. 260).
- (B4) CARBONACEOUS (p. 261).
- (B5) PHOSPHATIC (p. 273).

(B1). **CALCAREOUS DEPOSITS.** These comprise limestones built up by the accumulation of varied fossil (or recent) shell-fragments, corals, micro-organisms, etc., set in a matrix mainly of organic, to a lesser extent of inorganic origin. Distinctive types are determined by characteristic fossils, by peculiar structures or by the presence of particular compounds or impurities. Some degree of consolidation is common to all except the abyssal oozes conveniently considered here. Thus we may recognize:

- (B1.1) Limestone (including distinctive fossil types) (p. 245).
- (B1.2) Dolomitic Limestone (p. 250).
- (B1.3) Oolitic and Pisolitic Limestone (p. 251).
- (B1.4) Abyssal Ooze (p. 253).
- (B1.5) Chalk (p. 254).

(B1.1) LIMESTONE

[P1. 48 D, E, *between pp.* 208-209, and P1. 49A-D, *between pp.* 240-241]

Def. Limestone is the name applied to stratified rocks chiefly of organic origin and consisting substantially of calcium carbonate.

Lith. Extremely variable, depending primarily on the nature and quantity of fossil fragments present, on their degree of preservation

and cementation; also on the purity of the rock as determined by foreign matter or secondary constituents developed. Every gradation from fine, compact, close-grained type, void of recognizable organisms, to coarse shelly limestone occurs. Where organic remains are scanty or wanting and cement predominates, coarse to fine crystalline characters may be observed. In some examples composed of mutually interferent calcite crystals of megascopic size and uniformity of dimensions, the 'sugary' or 'saccharoidal' character is apparent. Contrasted are those types in which the rock is made up of a homogeneous aggregate of microcrystalline calcite particles, etc., with difficulty distinguishable lithologically from certain compact grits or quartzites. In doubtful cases the acid test should always be applied: with normal limestone effervescence when cold is marked.

Colour is a rough guide to purity; white, cream-coloured, yellow and pale grey rocks are normally the most free from detrital and other contamination; red limestone implies disseminated oxide of iron; brown to chocolate-brown developments are mainly produced by strong impregnation of limonite; dark grey to black types depend largely on finely disseminated carbonaceous matter; greyish-brown or ochreous rocks often imply the presence of considerable argillaceous matter. Appreciable amounts of detrital quartz result in gritty or sandy limestone; when excessive, the rock passes into calcareous sandstone or grit (p. 219). Bedding normally developed, but may not be apparent in hand-specimen; more commonly observed in the finer, non-shelly types. Limestones are frequently the host of metalliferous and other minerals which may in certain cases be conspicuous; mineral veins, *e.g.* silica, calcite, fluorite, etc., are often observed traversing the rock in all directions. Prominent structures determined by oolite or pisolitic developments are separately noticed (B1.3, p. 251).

The following are among the common organic contributors to these rocks, whose remains are often determinable megascopically: *brachiopoda*, *actinozoa* (corals), *crustacea* (in particular the *ostracoda*), *echinoderma* (including the *crinoidea*), *foraminifera* (in part), *mollusca* (lamellibranchs and gasteropods). *Algae*, *foraminifera*, *polyzoa* or *bryozoa* and more rarely *pteropoda*, are among the well-known micro-organic contributors to these rocks.

Text. Highly variable, entirely dependent on presence (or absence) and size of organic remains, also on degree of compaction of the cementing material. The average type is probably of medium texture; many unfossiliferous limestones are very close-grained, particles averaging 0.1-0.2 mm., and are thus fine-textured rocks.

Shape. Organic fragments tend to preserve something of their essential morphology, though brittle shells may be disintegrated into several highly angular parts by compaction of the rock. Crystalline cementing material exerts its inherent tendency to produce natural shape, though this may be prevented where there is excess of material. Detrital particles usually exhibit considerable rounding.

Min. Comp. Al. When detrital matter occurs, it usually consists of quartz, iron-ores (chiefly ilmenite), tourmaline, zircon and garnet, *i.e.*

the stable accessory minerals. In a few instances the detrital suite may be considerably enriched, *e.g.* contribution of material from submarine volcanic rocks, etc. Shallow-water limestones appear to contain most allogenic minerals. F. Smithson observes that limestones associated with sandstones tend to be richer in detrital minerals than the latter rocks, due possibly to preservation of the less stable minerals by protective calcite envelopments*.

Au. Calcareous mud, either in the form of finely divided amorphous material or as crystalline calcite: the latter may represent a product of recrystallization. Silica is sometimes chalcedonic, often crypto-crystalline, or may occur as secondary quartz frequently doubly terminated. Limonite, hematite, carbonaceous matter and/or argillaceous material common; locally fluorite (Derbyshire). With advent of magnesium carbonate, the rock passes into a dolomitic limestone, type B1.2 (*q.v.*, p. 250).

Organic Material. This may imply the presence of calcite, aragonite, less commonly of silica. Calcareous *algae* are composed either of calcite or aragonite; similarly the corals (*actinozoa*) and *polyzoa*. *Crustacean* tests are mainly calcite, chitinous material, less commonly phosphate of lime; *brachiopoda* and *echinoderma* are of calcite, similarly the vitreous forms of *foraminifera*; the porcellaneous forms of the latter are probably of aragonite in most cases. *Lamellibranchia* vary, certain genera (*e.g.* *Trigonia*, *Pinna*, *Spondylus*, *Unio*, etc.) exhibiting an inner shell-layer of aragonite, the outer being of calcite; *Ostrea*, *Pecten*, etc., are entirely of calcite, otherwise many forms are composed of aragonite. *Gasteropoda* are mainly of aragonite; a few combine both minerals (*e.g.* *Littorina*). *Fusinus* is entirely of calcite. *Pteropoda* are chiefly aragonite. *Porifera* (sponges) are composed both of calcite (calcareous sponges) and silica. Most *cephalopod* remains are composed of aragonite, but the guard of *belemnites* is of calcite. Replacement of such original organic substance by silica, limonite, marcasite or pyrite, rarely by calcium sulphate, barite, etc., is possible.

Mech. Comp. Concerns only detrital ingredients which are usually very fine, 0.1–0.01 mm.

Micro. Investigations of limestones in thin section should proceed methodically. Where organic remains are present, study these first. The arrangement of the mineral substance forming the shells or hard parts may be concentric, radial, tangential or combinations of these. Radial arrangement results in the 'black cross' effect in doubly polarized light. Sometimes the shell-fragments are thick, cloudy or opaque. Micro-organisms, *e.g.* *foramanifera*, *algae*, *radiolaria*, *diatoms*, etc., are always significant and often well preserved, either as original carbonate or silica, or replaced by pyrite, glauconite, etc. Calcite and aragonite as fossil-shell substance are often impossible to differentiate positively under the microscope: see p. 68. Next investigate the matrix of the rock. If megascopic or larger microscopic organisms are plentiful, this may be reduced to enveloping or interstitial material; with impoverishment of visible organisms, the matrix dominates and

* Written communication.

characterizes the rock. Usually it presents a mosaic of mutually inter-fert calcite crystals representing coarsely or finely recrystallized calcareous mud; sometimes the muddy character prevails, when much of the cement appears optically inert; nevertheless it shows up well by reflected light. Veins of secondary silica, deep bluish-grey birefringence tint, or of interlocking quartz crystals, may also traverse the rock, or may be distributed haphazardly in the calcite cement. Colouring matter denotes impurity, usually due to iron compounds. Detrital matter should be searched for under high power objective in the cementing medium (alternatively isolated by crushing the rock (Vol. I, Ch. III, p. 127); this examination may also reveal minute organisms scattered through the mass. Every transition from the normal limestone to dolomitic, oolitic and other types must be anticipated and will be easily decipherable under the microscope. The structure of limestones is primarily determined by the relationship of organic fragments or of prolific micro-organisms to the matrix or, where organisms are lacking, by arrangement of the components of the matrix, presence or absence of definite orientation, or by special developments (e.g. oolites, p. 251). Careful scrutiny of the closeness or sparseness of spacing of the fossil elements in the cement is significant, often diagnostic for a particular horizon in the limestone formation. Similarly the manner of distribution of micro-organisms in a finely divided matrix should be noted. Secondary structures determined by mineral veins, argillaceous matter in bands, patches of siliceous material, chert development, etc., should all be carefully investigated and recorded.

The results of microscopic examination, by determination of specific organisms characteristic of the rock, lead to its correct definition. Thus the following varieties may be separated, each distinguished by the presence to a greater or lesser extent of the forms identified:

- (a) *Algal limestone*, e.g. *Lithothamnion* and *Chara* limestones.
- (b) *Bryozoan limestone*, e.g. *Fenestella* limestone.
- (c) *Coral limestone*, e.g. *Alveolite* limestone.
- (d) *Crinoidal limestone*, e.g. *Encrinite* (*Encrinus*) limestone.
- (e) *Crustacean limestone*, e.g. *Ostracod* limestone.
- (f) *Echinoid limestone*, e.g. *Nucleolite* (*Echinobrissus*) limestone.
- (g) *Foraminiferal limestone*, e.g. *Nummulitic* limestone.
- (h) *Shelly limestone*, made up largely of miscellaneous fossil-shell fragments, chiefly *mollusca* and *brachiopoda*.

With increase of impurity in the form of argillaceous matter, the so-called 'argillaceous limestone' or 'cement-stone' is produced. This variety embodies the normal features of limestone, but the matrix contains a good deal of finely divided clay-substance, much of it optically inert; sometimes the clay-substance is distributed regularly throughout the rock, in other cases it occurs in patches, often enclosing visible detrital quartz.

Types. Cambrian, Durness Limestone, N.W. Highlands of Scotland, Skye, etc., with sponge remains, sometimes partially dolomitized,

some examples 'saccharoidal'¹; Ordovician, Bala Limestone, Bala, North Wales, with calcareous and siliceous mud, crinoids, polyzoa, etc.²; also the Corona Beds (of same age), Cross Fell, Westmorland, crustacean limestone (*Beyrichia*)³; Silurian, Wenlock Limestone, Shropshire, often impure rock with abundant corals, also crinoids and polyzoa⁴; Aymestry Limestone, Silurian, Shropshire, earthy limestone with brachiopods (*Pentamerus (Conchidium)* Limestone)⁵; Devonian limestone, Devonshire, corals and crinoids⁶; Old Red Sandstone 'Cornstone', Welsh Borders, nodular, argillaceous limestone, much amorphous matter⁷; Carboniferous Limestone, Bristol district, Forest of Dean, etc., crinoidal and shelly limestone⁸; Lias, Barrow-on-Soar, Leicestershire, argillaceous limestone ('Cement Stone') with shell-fragments, fish scales, etc.⁹; Portlandian, massive limestone, often with much calcareous mud, shell-fragments, secondary silica etc.¹⁰; Purbeckian (Upper Purbeck) 'Marble', Dorset, Wiltshire, etc.; freshwater limestone with gasteropod (*Paludina*) and lamellibranch fragments (*Cyrena*, *Unio*, etc.), also plant remains¹¹; Eocene, Cairo, Egypt, foraminiferal limestone ('Nummulitic Limestone')¹²; Oligocene, Bembridge Limestone, marly or concretionary, freshwater limestone with *algae* (*Chara*), gasteropods and curious oviform bodies, said to be 'the eggs of the large *Amphidromus*'¹³.

References

- ¹ Geology N.W. Highlands, *Mem. Geol. Surv. Scot.*, 1907, p. 375.
- ² A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, p. 125.
- ³ J. E. Marr, *Geol. Mag.*, 1892, p. 97.
- ⁴ A. J. Jukes-Browne, *op. cit.*, p. 165; A. Harker, *Petrology for Students* (University Press, Cambridge), 1954, p. 226.
- ⁵ A. J. Jukes-Browne, *op. cit.*, p. 167.
- ⁶ E. Wethered, *Quart. Journ. Geol. Soc.*, **48**, 1892, p. 377.
- ⁷ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 504.
- ⁸ E. Wethered, *Geol. Mag.*, 1886, p. 529.
- ⁹ Author's observations.
- ¹⁰ F. H. Edmunds and R. J. Schaffer, Portland Stone, etc., *Proc. Geol. Assoc.*, **43**, 1932, p. 225.
- ¹¹ W. R. Andrews and A. J. Jukes-Browne, *Quart. Journ. Geol. Soc.*, **50**, 1894, p. 59 (Vale of Wardour); A. Strahan, *Geology of Isle of Purbeck*, *Mem. Geol. Surv.*, 1898, pp. 79, 80; H. B. Woodward, *Jurassic Rocks of Britain*, *Mem. Geol. Surv.*, **5**, 1894; W. J. Arkell, *The Geology of the Country around Weymouth*, etc., *Mem. Geol. Surv.*, 1947, ch. 7.
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T. Robertson and ors., *The Limestones of Scotland*, *Mem. Geol. Surv. Spec. Rep. Min. Res.*, **35**, 1949, especially Chs. 4 and 5.

(B1.2) DOLOMITIC LIMESTONE

[Pl. 49E, F, *between pp. 240–241*, and Pl. 50A, *between pp. 240–241*]

Def. A limestone containing a substantial proportion of dolomite.

Lith. The true dolomitic limestone is one containing the mineral dolomite, but in which calcium carbonate predominates. In outward appearance there is often nothing specific to suggest the presence of dolomite and even under the microscope, if the familiar dolomite 'rhombs' are not developed, diagnosis may not be positive in the absence of chemical test (p. 68). On the other hand, many dolomitic limestones are sufficiently distinctive in microscopical characters to warrant the separation of the type from ordinary limestones. Megascopic characters of dolomitic limestones include compactness, closeness of grain, cellular structure, usually a white, cream or grey colour; their appearance *en masse* is often nodular, concretionary, thick bedded, conspicuously jointed, sometimes massive. Organic remains are common, but may be obliterated by dolomitization; they often show a tendency to weather out on the surface of the rock, *e.g.* sponge limestone (Durness dolomitic limestone, Skye, N.B.)¹. Bedding may or may not be apparent in the hand-specimen.

Text. Usually medium to fine; sometimes earthy.

Shape. Concerns detrital particles only: usually rounded. In so far as dolomite is concerned, this mineral often builds very perfect rhombs, producing a highly angular mosaic.

Min. Comp. Al. As for limestone (B1.1, p. 246).

Au. Calcite, dolomite, silica, hematite, limonite, less commonly argillaceous matter and carbon; also sulphates.

Organic material. As for limestone, but *foraminifera*, corals and *polyzoa* tend to predominate.

Mech. Comp. Detrital constituents usually very fine: < 0.05 mm.

Micro. Under the microscope every stage from incipient to partial or complete dolomitization can be traced. Incomplete dolomitization usually implies the change subsequent to deposition of the original limestone; complete dolomitization may denote contemporaneous process with deposition. In the case of complete achievement, much of the original organic remains may be obliterated and specific identification be thereby rendered impossible; in such examples the dolomite assumes a crystalline or granular form. Where partial change is manifest, the dolomite is detected for the greater part in the matrix; if crystalline (in rhombs) it will at once be apparent; if granular or disseminated as fine dolomitic mud, it may be amorphous or almost cryptocrystalline, when staining will be necessary for its differentiation from calcite. In some examples dolomite rhombs or other crystal forms show the presence of impurities such as hematite, arranged in geometrical fashion sympathetically with the outlines of the crystals. Secondary silica is often noted in the interstices of the crystals. Alternatively, where the limestone was originally impure with admixture of argillaceous matter, this is seen to form a dirty, usually impenetrable background to the dolomite mosaic. Dolomitization

of oolite limestone is not uncommon. Secondary silicification of dolomitic limestone also occurs. Another feature of this type of limestone is the presence of cracks, sometimes widened to gaps of large size, which may or may not be filled with secondary calcite, quartz or other mineral, *e.g.* barite, anhydrite; such veins are in the nature of shrinkage-cracks, determined by the volume-contraction of 12.3% with complete dolomitization. The association of anhydrite, gypsum, rock-salt etc., with certain dolomitic limestones suggests inorganic origin, *i.e.* precipitation in land-locked saline water (p. 442).

Types. Cambrian, Durness Limestone, N.W. Highlands of Scotland, Skye, etc., pure limestone with sponge remains, partial dolomitization¹; Devonian limestone, Devonshire, partial dolomitization with rhombs picked out with iron oxide²; Permian Magnesian limestone, complete dolomitization, granular dolomite, few organic remains recognizable³; Triassic Dolomites, Southern Tyrol, massive, unstratified dolomitic limestone, chiefly algal and echinoderm organisms⁴.

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- ¹ Geology N.W. Highlands, *Mem. Geol. Surv. Scot.*, 1907, p. 375.
- ² E. Wethered, *Quart. Journ. Geol. Soc.*, **48**, 1892, p. 377.
- ³ D. Woolacott, *Quart. Journ. Geol. Soc.*, **67**, 1911, p. 312; also *Geol. Mag.* 1919, pp. 452, 485.
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(B1.3) OOLITIC AND PISOLITIC LIMESTONE

[Pl. 50B-D, between pp. 240-241]

Def. Oolitic limestone is characterized by spheroidal or ellipsoidal grains of calcium carbonate built up concentrically about a nucleus, *e.g.* quartz grain, shell fragment.

Pisolitic limestone is a coarse variety of oolitic limestone in which the individual grains attain the size of a pea.

Lith. These are special but commonly developed types of limestone in which the bulk of the rock is composed of spheroidal or ellipsoidal grains of calcium carbonate; such grains exhibit concentric (successive) growths of the carbonate about an organic or inorganic nucleus. The smaller developments, 1 mm. (or less)—2 mm. in diameter, are the oolites; larger grains, up to the size of a pea or even larger, are the pisolites. Very coarse pisolites are sometimes erroneously termed 'grits', *e.g.* 'Pea Grit'. Both types are readily recognized by these

distinguishing megascopic characters. The oolites and pisolites may be closely packed together, or they may be scattered haphazardly through a finer matrix. Organisms extremely common. Bedding frequent. Colour varies from white in the purest forms of limestone to yellow, brown and red. Secondary calcite and/or silica often noted in the hand-specimen.

Text. Coarse to medium; rough; earthy or rubbly with conspicuous matrix.

Shape. Oolites spheroidal or ellipsoidal; pisolites more irregular, sometimes flattened resembling large nummulites. Detrital constituents SA.

Min. Comp. Al. Quartz, iron-ores and often surprisingly varied accessory mineral suite in the impure types.

Au. Calcite, siderite, dolomite, silica, hematite, limonite. Oolites and pisolites of fine calcareous mud, sometimes crystallized; silicified oolites not uncommon.

Organic Material. Shell-fragments, *foraminifera*, crinoid stems, *polyzoa*, etc.

Mech. Comp. Detrital constituents usually of the silt grade. Oolite and pisolite dimensions as above.

Micro. Oolite and pisolitic limestones, especially the former, are among some of the most striking varieties of sedimentary rocks met with under the microscope. The oolites themselves first attract attention; examine for nucleus, which may be a detrital quartz grain, shell-fragment or *foraminifera*; in many cases it is represented by a mud particle; sometimes no nucleus is determinable. Concentric layers of carbonate are revealed, often picked out by ferriferous impurity; in some examples radial structure is observed. These oolite grains, together with shell-fragments and free organisms, are set in a fine matrix which, in the purest types, is seen to be composed of a crystalline mosaic of calcite occurring in mutually interferent particles; this matrix is frequently stained with limonite or hematite and spotted with iron oxide. Quartz is common, increasing with the more earthy types. Sometimes much of the centre of the oolite grain is replaced by calcite of the same character as the matrix. The foregoing remarks apply equally to the pisolitic types. Some oolitic limestones exhibit partial, if not complete dolomitization. In structure, apart from the special developments under discussion, note should be taken of the proportion of oolites or pisolites to matrix; where the latter predominates derivation of the former from pre-existing oolitic or pisolitic rocks may be suggested.

Types. Ordovician, Hirnant Limestone, Bala district, N. Wales, oolites partly replaced by chalcedonic silica and layers picked out with carbon dust¹; Silurian, Wenlock Limestone, Malvern, oolites scattered in calcareous-argillaceous matrix²; Carboniferous Limestone, Gloucestershire, etc., oolitic rock with *Girvanella*³; Inferior Oolite, Gloucestershire, both oolitic and pisolitic examples, the former with abundant organic remains, the latter ('Pea Grit') characterized by *Girvanella*⁴; Great Oolite, Malton, Yorkshire, Northamptonshire, etc., scattered oolite grains in recrystallized calcite matrix⁵; also Bath Oolite (Great Oolite), Bath, Somerset, compact oolitic type⁶; Corallian, Osmington

Oolite, a perfect example of a closely packed, pure oolite⁷; Portlandian, Portland Oolite, Portland, Dorset⁸.

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- ^{2, 5, 6} Author's observations.
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- ⁴ E. Wethered, *loc. cit.*, p. 274.
- ⁷ J. H. Blake and W. H. Hudleston, *Quart. Journ. Geol. Soc.*, 33, 1877, p. 265; E. Wethered, *loc. cit.*, p. 278; A. Strahan, Geology of the Isle of Purbeck, etc., *Mem. Geol. Surv.*, 1898, p. 37; W. J. Arkell, The Geology of the Country around Weymouth, etc., *Mem. Geol. Surv.*, 1947, Ch. 7.
- ⁸ G. F. Harris, *Proc. Geol. Assoc.*, 14, 1895, p. 72.

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(B1.4) ABYSSAL OOZE (CALCAREOUS)

[Pl. 50E, between pp. 240–241]

Def. Ooze (calcareous) is a soft, incoherent deep-sea deposit composed for the most part of the hard parts of micro-organisms such as foraminifera.

Lith. Under this heading is included all deep-sea oozes of predominantly calcareous character. They are in the main composed of the hard parts of free-swimming pelagic organisms such as *foraminifera*. The two important examples are Globigerina Ooze and Pteropod Ooze. Dredged samples (e.g. Challenger Expedition) are white to buff-coloured when dry and have the appearance of very fine powder. The organisms are usually too minute to be seen with the naked eye.

Text. Exceedingly fine, homogeneous, 'soapy'.

Shape. Detrital particles, when present, A.

Min. Comp. Al. Felspar, augite, olivine, hornblende, quartz, magnetite, volcanic glass, rock-fragments, etc.

Au. Calcium carbonate, silica, magnesite, traces of phosphate, sulphate.

Mech. Comp. Detrital and other inorganic particles < 0.01 mm. but highly variable.

Micro. Globigerina ooze is composed principally of the tests of *globigerina* and other *foraminifera*, usually with a small proportion of siliceous organisms, e.g. *radiolaria*, *diatoms*. In addition characteristic disc-like bodies termed *coccoliths* are observed; these are calcareous parts of certain minute planktonic algae (*coccolithophoridae*). Another form of similar origin is the *rhabdolith*, a long slender T-shaped body, not unlike a sponge spicule. Organic matter makes up the bulk of the fine washings of this ooze, though the mineral constituents are normally quite conspicuous, constituting from 3% to 4%. The inorganic matter resembles the abyssal red clay (see A3.5, p. 234). Pteropod ooze is composed principally of *pteropod* shells and *heteropod* (pelagic

gasteropods), together with *foraminifera* and a small percentage of siliceous organisms. This type of ooze is much more variable in character than the globiferina ooze, though there is about the same amount of mineral matter; *coccoliths* and *rhabdoliths* are also found. Both the pteropod and heteropod shells are very delicate and exhibit beautiful forms; much broken and fragmental material is characteristic. Samples relieved of the fine calcareous mud by careful washing are best studied with a binocular microscope, using dark-ground illumination.

Types. Globigerina and Pteropod Ooze, Challenger Expedition¹.

Reference

- ¹ J. Murray and A. F. Renard, Deep Sea Deposits, *Challenger Report*, 1891.

(B1.5) CHALK

[Pl. 50F, between pp. 240-241]

Def. A fine textured foraminiferal limestone, substantially pure calcium carbonate, of Cretaceous age, as developed in the British Isles and North-West Europe.

Lith. An exceedingly pure form of limestone (calcium carbonate) varying from soft, almost incoherent material to compact, hard rock. White, yellow to grey in colour, the latter implying some admixture of clay material; strongly glauconitic varieties are greenish-grey. Usually homogeneous and well stratified, but bedding not apparent in small specimens. Megascopic organisms are mainly molluscan fragments, especially parts of *Inoceramus*; many other fossils, however, are characteristic, often beautifully preserved. Calcite veins observed in the harder varieties. Flint nodules and marcasite concretions common at certain horizons. Black staining, detritic patterning, usually on joint-surfaces, due to manganese oxide.

Text. Fine, compact or friable.

Shape. Detrital particles A to SA. Quartz often well rounded.

Min. Comp. Al. Rare. Quartz, ilmenite, tourmaline, zircon, staurolite, locally chromite (p. 81).

Au. Calcareous mud, secondary silica, limonite, glauconite.

Mech. Comp. Chalk particles are exceedingly fine in grade and remain suspended in water for considerable time. Detrital grains usually < 0.01 mm.

Micro. Hard chalk is best studied by means of thin sections in addition to its investigation in the form of powdered material. The softer varieties are examined as incoherent rocks and may with advantage be washed free of much of the finest mud. For inorganic components the soluble carbonate should be eliminated with acid and the residue segregated. Microscopical examination of chalk shows that it is made up partly of micro-organisms, mainly of very fine calcareous matter and, in the impure varieties, of clay-substance and detrital minerals; the latter are normally scanty. Micro-organisms include *foraminifera*, especially chambers of *globigerina*, also cells and spikes of planktonic algae known respectively as *coccoliths* and *rhabdoliths*

(p. 253), sponge spicules and less commonly *radiolarian* tests. The fine white mud may be due to disintegrated fossil shells or possibly to precipitation from solution. Glauconite frequently fills the chambers of the *foraminifera* present, or otherwise preserves original structures; its partial alteration to limonite is often observed. Other infilling material may be calcite, in well crystallized mosaic, or chalcedonic silica.

Types. Cretaceous: Lower Chalk, Wiltshire, Dorset etc., 'Chloritic Marl', a sandy, glauconitic variety¹; Chalk Marl, with clay material¹; 'Belemnite Marl', a soft grey chalk with belemnites (*Actinocamax plenus*) etc.²; 'Totternhoe Stone', dark grey chalk with green-coated nodules (base) and abundant shell-fragments up to 60% or 70% of the rock³; Middle Chalk, white, nodular, rough or lumpy; 'Melborne Rock', hard, nodular chalk⁴; Upper Chalk with flints, white, powdery, nodular or in layers⁵. (N.B.—The so-called 'Red Chalk' of Hunstanton, Norfolk, is of Selbornian age, and consists of an argillaceous limestone containing abundant red oxide of iron^{6,7}.)

References

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- ² W. Hill, *Quart. Journ. Geol. Soc.*, 44, 1888, p. 320.
- ³ A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, p. 504.
- ⁴ W. Hill and A. J. Jukes-Browne, *Quart. Journ. Geol. Soc.*, 42, 1886, p. 216.
- ⁵ Author's observations.
- ⁶ W. Hill, *loc. cit.*, 1, 1900, p. 345.
- ⁷ R. H. Rastall, *Geol. Mag.*, 67, 1930, p. 436.

General References

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 W. Hume, *Quart. Journ. Geol. Soc.*, 53, 1897, p. 568.
 W. A. Tarr, *Geol. Mag.*, 62, 1925, p. 252.
 I. C. Double, *Journ. Roy. Micros. Soc.*, 1927-8.
 L. Cayeux, *Les Roches Sédimentaires de France: Roches Carbonates*, (Masson, Paris), 1935.

(B2) SILICEOUS DEPOSITS. This division includes consolidated rocks such as chert and flint, the abyssal oozes depending mainly on the accumulation of organisms such as *radiolaria*, diatoms and sponge skeletons and the curious 'silica earth' deposits, likewise of organic origin. In the case of chert and flint it is now generally admitted that the entirely organic origin of these deposits is open to question; silica derived from chemical reaction may and often does play an important part in their formation (p. 281). For the most part, however, these deposits exhibit so much definitely identifiable organic matter that its predominating influence is seldom in doubt. The following types are recognized:

- (B2.1) Chert and Flint (p. 256).
- (B2.2) Abyssal Ooze (p. 257).
- (B2.3) Siliceous Earth (p. 258).

(B2.1) CHERT AND FLINT*

[Pl. 50A-C, between pp. 240-241]

Def. Chert is a compact cryptocrystalline rock composed essentially of chalcedonic silica and microcrystalline quartz and characterized by a splintery fracture. The type is not restricted to any particular stratigraphical horizon. Flint is similar to chert in composition, but is more dense and normally exhibits much less microcrystalline quartz, except in weathered examples. Flint is usually restricted in Britain to the Cretaceous (Chalk) developments and to its occurrence in deposits derived therefrom; it is characterized by a marked conchoidal fracture.

Lith. The difference between chert and flint is probably more apparent than real and to some extent is a matter of nomenclature. Both rocks are essentially pure developments of chalcedonic silica occurring in the form of nodules, concretions or bedded layers in calcareous deposits such as limestone. In British stratigraphy the term 'chert' applies for the most part to such rocks present in pre-Chalk horizons; flint is restricted to the real Chalk occurrences and to those rudaceous deposits derived therefrom. In external appearance both chert and flint are very similar when fresh, though the former has a more decided splintery fracture, the latter a conchoidal fracture and a tendency to exhibit the complementary 'bulb of percussion' (unlike chert). When fresh, both flint and chert may be blue-grey or indigo in colour; weathering and exposure to atmospheric conditions bring about obvious changes both in colour and appearance (patination). Chert often assumes a 'sugary' appearance; flint, a worn, pale-coloured porcellaneous aspect. Chert is often traversed by a network of cracks filled with secondary silica and stained with limonite or hematite; flint is less commonly susceptible to these developments. The interior of a chert nodule is usually solid, often a fossil-shell nucleus or aggregate of fossil particles; the interior of a flint, on the other hand, may be quite hollow and from it a siliceous powder, full of sponge spicules, etc., may often be obtained.

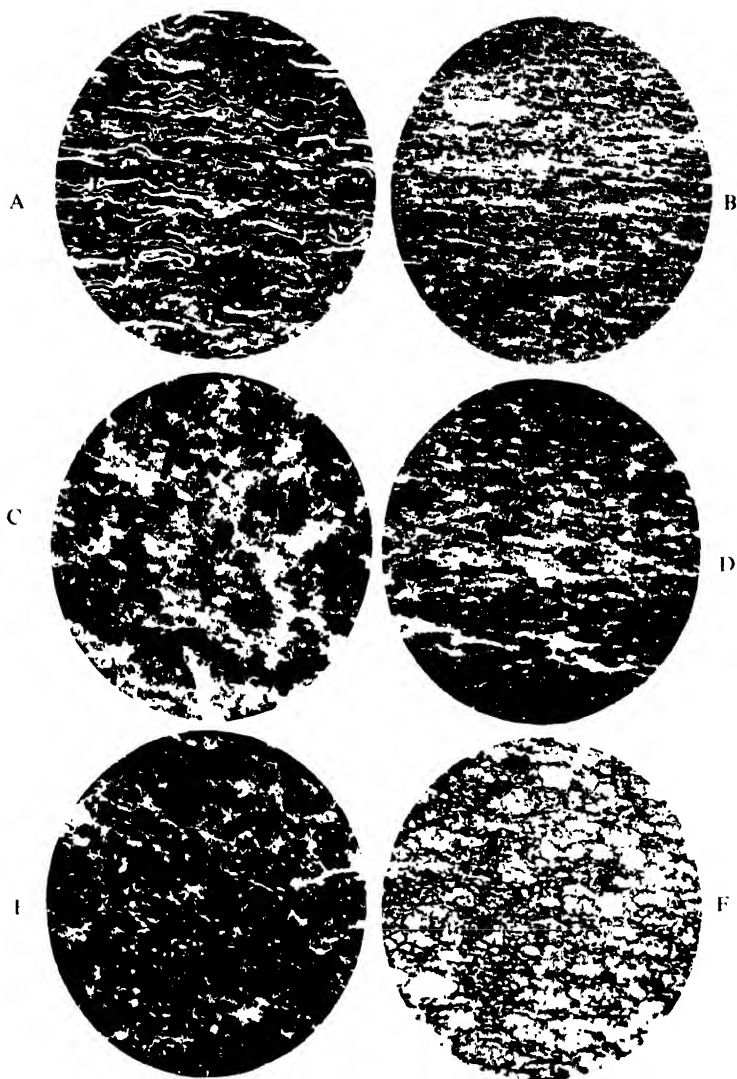
Text. Extremely fine, smooth; rough on weathered surface.

Shape. As nodules or concretions, both chert and flint assume diverse shapes, often occurring in most fantastic forms.

Min. Comp. Silica, mainly chalcedony; in flint occasionally opaline silica. Limonite staining.

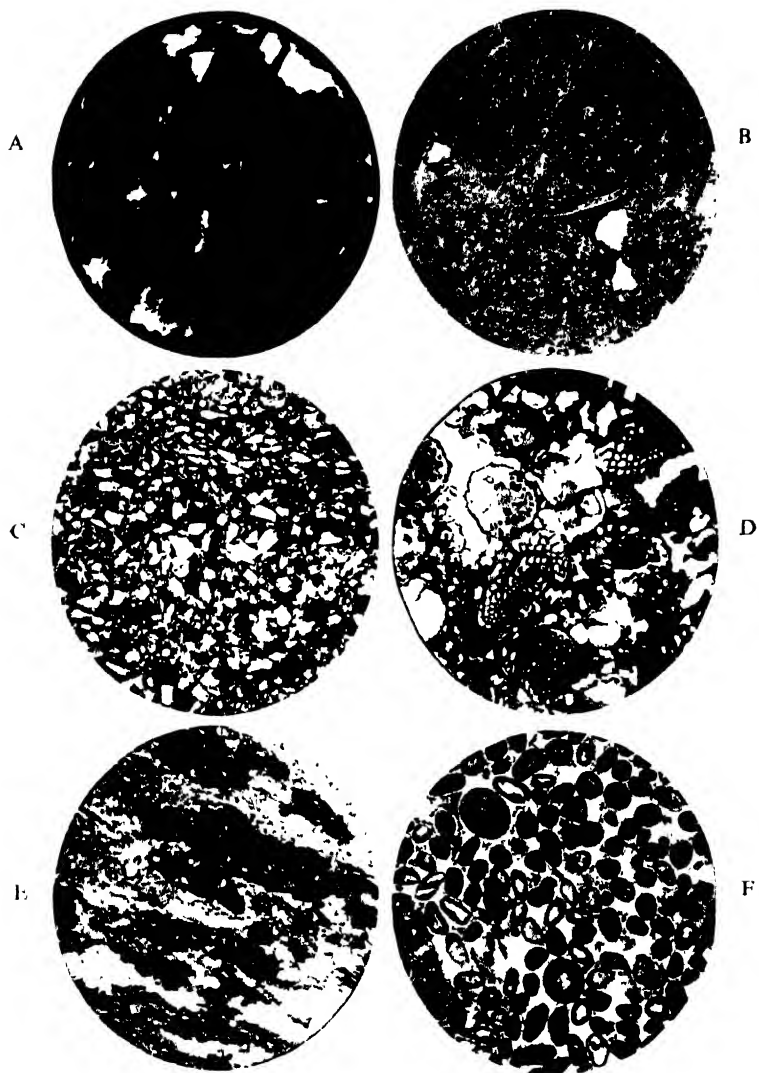
Micro. The microscopical examination of chert depends largely on the age of the material and on its condition as regards weathering. Some varieties, *i.e.* Portland Chert (Upper Jurassic), as with flint from the Upper Chalk, are almost optically inert and very little, save certain ill-defined organic remains, can be made out. In most cases, however, some degree of crystallization or cryptocrystalline structure can be ascertained, especially in cherts. When well preserved, the spherical tests of *radiolaria*, or characteristic sponge spicules, are easily diagnosed, but in many so-called radiolarian cherts, the dominant

* Only in part referable to organic origin: see p. 281.



OIL-SHALE

- A "Tasmanite," Tasmania [x 25]
- B Oil-shale (Carboniferous), Oakbank, Linlithgow, N.B. [x 25]
- C do (Kimmeridgian) Kimmeridge, Dorset, bedding [x 15]
- D do do do do \perp bedding. [x 15]
- E "Kuggersite" (Ordovician), Esthonia [x 40]
- F Oil-shale, Blue Mountains, New Zealand [x 22]



ASPHALT AND BITUMEN IMPREGNATED ROCKS

- A Asphalt, "Pitch Lake", Trinidad [x 48]
- B do Roumania [x 15]
- C Impregnated Sandstone, Pechelbronn, Alsace [x 23]
- D do *Fusulina* Limestone, Szran, Simbirska, Russia [x 11]
- E Impregnated Limestone, Dept of Gard, France [x 15]
- F do Oolitic Limestone, Hanover [x 25]



B



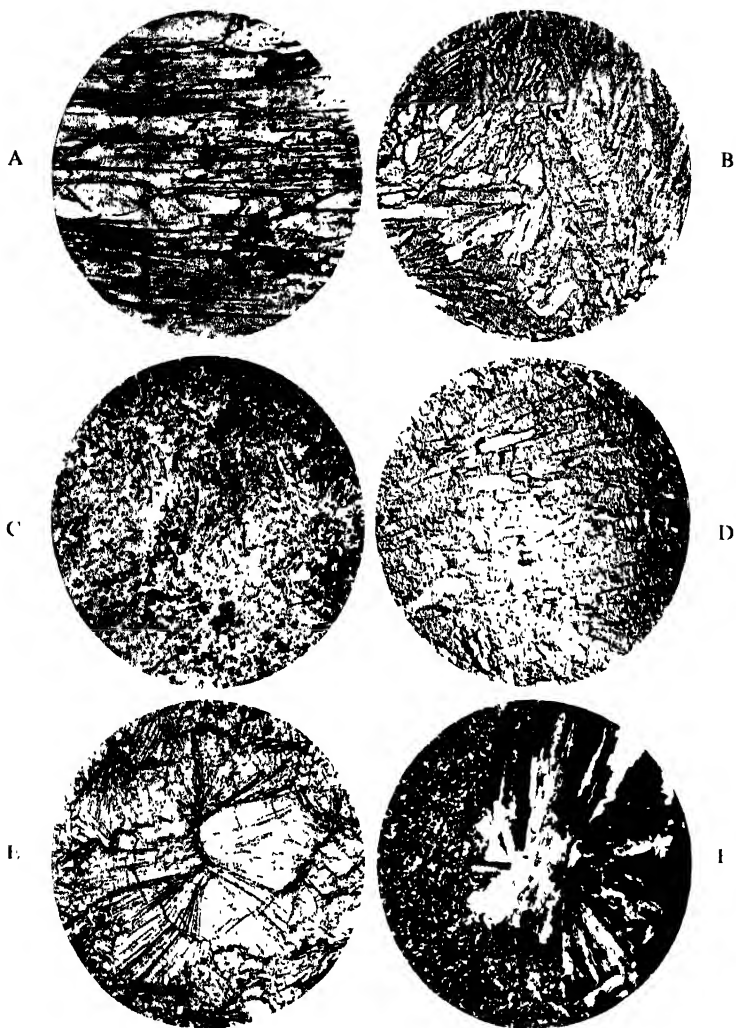
D



F

PHOSPHATES AND BIDDIED IRON-ORES

- A. Calcium Phosphate Nodule, Oshosun, Nigeria [x 50.]
- B. Phosphate Rock, Oshosun, Nigeria. [x 5.]
- C. Cleveland Ironstone (Liassic), Yorks [x 23]
- D. Ironstone (Estuarine), Thrapston, Northants [x 25]
- E. Abbotsbury Iron-Ore (Corallian), Abbotsbury, Dorset [x 15]
- F. Pyritic Blackband (Coal Measures), Powell Duffryn, N. Wales [x 14]



CHLORIDE AND SULPHATE

- A Rock-Salt (Triassic), Cheshge [x 15]
 B Anhydrite, Cropwell Bishop, Notts [Bladed Type, x 15]
 C do Cote Hill, Cumberland [Granular Type, x 23.]
 D do Cropwell Bishop, Notts [Foliated Type x 15]
 E do Segeberg, Germany [Spherulitic (radial) Type x 15.]
 F Anhydrite-Gypsum Rock (Permian) Hatfield, nr. Doncaster, Yorks
 [Crossed Nicol, x 25]

organism is only represented by a blurred spherical structure which has to be taken very much on trust. Every stage between the inert chalcedonic silica, the faint reaction between crossed nicols, to the fine mass of mutually interferent silica particles of brilliant blue-grey or yellow polarization tints, is discernible in cherts; flint seldom exhibits striking polarization of phenomena unless markedly weathered. Chert replacement of oolitic or shelly limestone is not uncommon.

Types. Ordovician, Radiolarian Chert, South Scotland¹; Radiolarian Chert of same age (?), Mullion Island, Cornwall²; Portland Chert, Dorset³; Upper Cretaceous flint (zone of *Micraster coranguinum*, Upper Chalk), Kent, Cambridgeshire, etc.⁴; Pleistocene gravels from Thames basin: flints showing different degrees of weathering, some with hollow centres, spicule-dust, etc.⁵; G. M. Lees has described some interesting brecciated, banded and replacement cherts from Palestine, the latter type including some remarkable coprolite silicifications⁶.

References

- ¹ G. J. Hinde, *Ann. Mag. Nat. Hist.*, **6**, 1890, p. 41; C. Lapworth, *Geol. Mag.*, 1889, pp. 20, 69.
- ² G. J. Hinde, *Quart. Journ. Geol. Soc.*, **49**, 1893, p. 215; H. Fox and J. J. H. Teall, *Quart. Journ. Geol. Soc.*, **49**, 1893, p. 211; J. S. Flett and J. B. Hill, *Geology of the Lizard, etc.*, *Mem. Geol. Surv.*, **359**, 1912, p. 172 and refs. cited.
- ³ A. Strahan, *Geology of the Isle of Purbeck, etc.*, *Mem. Geol. Surv.*, 1898.
- ⁴ W. Hill, *Cretaceous Rocks of Britain*, *Mem. Geol. Surv.*, **3**, 1904.
- ⁵ Author's observations.
- ⁶ G. M. Lees, *Proc. Geol. Assoc.*, **39**, 1928, p. 445.

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- W. Hill, *Proc. Geol. Assoc.*, **22**, 1911, p. 61.
 W. A. Tarr, *Origin of Chert*, *Amer. Journ. Sci.*, **44**, 1917, p. 413.
 W. A. Richardson, *Geol. Mag.*, 1919, p. 535.
 W. A. Tarr, *The Origin of Chert and Flint*, *Univ. of Missouri Studies*, **1**, 1926, p. 2.
 W. H. Twenhofel, *Treatise on Sedimentation* (Bailliere, Tindall and Cox, London), 1932, p. 519.
 W. A. Tarr, *Terminology of Chemical Siliceous Sediments*, *Comte. on Sedimentation*, *Nat. Research Council*, 1936.

(B2.2) ABYSSAL OOZE (SILICEOUS)

[Pl. 51D, E, between pp. 240-241]

Def. Ooze (siliceous) is a soft, incoherent deep-sea deposit composed for the most part of the hard parts of micro-organisms such as radiolaria, diatomacea, etc.

Lith. Ooze of siliceous character owes its origin chiefly to radiolarian tests, diatom frustules or sponge spicules, or to a combination of these. Such ooze is seldom pure, but contains admixture of calcareous organisms (B1.4, p. 253) and volcanic mud (A3.2, p. 231). The organisms are not discernible with the naked eye; the material is homogeneous, white, yellow or red in colour and of the consistency of flour. Normally incoherent when dry.

Text. Extremely fine.

Shape. Detrital particles A.

Min. Comp. Al. Quartz, felspar, augite, hornblende, fragments of pumice, magnetic iron ore particles, volcanic rock-fragments, etc.

Au. Silica, oxide of iron, calcareous matter, manganese grains, etc.

Mech. Comp. Detrital grains 0.15–0.01 mm. or less.

Micro. Under the microscope radiolarian ooze is characterized by the tests or skeletons of these organisms; such skeletons exhibit either lattice-like or reticulate structure and are usually spherical, elongated and with or without spines. These organisms constitute 20% of the ooze (or more) in typical examples. In the diatom ooze, the siliceous frustules of these vegetable organisms occur in spherical, polygonal, vermiform and other shapes and are associated with calcareous organisms and terrigenous matter. Sponge ooze is a distinctive deposit, composed principally of spicules of varying shape, 3-rayed, 4-rayed, multi-rayed types, etc., or as single spicules (monaxonid). Most of these spicules are isotropic between crossed nicols, though with process of time cryptocrystalline silica is noted. The washings from siliceous ooze are made up chiefly of calcareous and siliceous mud in about equal proportions.

Types. Radiolarian Ooze, Pacific and Indian Oceans etc.¹; Diatom Ooze, Indian Ocean, North Atlantic Ocean etc.²; Sponge Ooze, various deep-sea deposits³.

References

¹ J. Murray and A. F. Renard, *Deep Sea Deposits, Challenger Report*, 1891, p. 203.

² *Ibid.*, p. 208.

³ Author's observations.

(B2.3) SILICEOUS EARTH

[Pl. 51F, between pp. 240–241 and Fig. 47, p. 259]

Def. Siliceous Earth is a group term denoting certain types of siliceous deposit, mainly of organic origin, e.g. diatomaceous earth.

Lith. Within this category fall the following rocks: Radiolarian Earth, Barbados Earth, Diatomaceous Earth (Diatomite – Kieselguhr), Infusorial Earth (of much the same composition as Diatomite). Tripoli, sometimes confused with diatomaceous earth, is a residual product derived from decomposition of siliceous limestone. These earths are fundamentally similar to the oozes (B2.2), but are formed under different conditions and, moreover, are partially consolidated. For instance, diatomite is produced by the accumulation of diatom frustules in shallow lakes and swamps in contrast to the abyssal environment of the ooze composed of much the same organic material. The earths are usually white, cream, or when impure highly coloured, buff, brown, red; they are homogeneous, porous, pulverulent and have a decidedly earthy 'feel' and appearance.

Text. Very fine, powdery, friable, earthy.

Shape. A.

Min. Comp. Al. Usually a conspicuous detrital assemblage varying

considerably in nature and quantity. Quartz, iron-ores, zircon, tourmaline, garnet, etc.

Au. Silica, limonite, hematite, calcareous matter, carbonaceous matter, manganese, etc.

Mech. Comp. Often remarkably uniform, ± 0.05 mm.

Micro. Most examples of these particular rocks can be studied both in thin section and as incoherent materials. Radiolarian earth is composed principally of radiolarian tests (p. 257), diatom frustules and sponge spicules; calcareous organisms are infrequent or absent but calcareous matter is invariably detected by the 'twinkling' reaction.

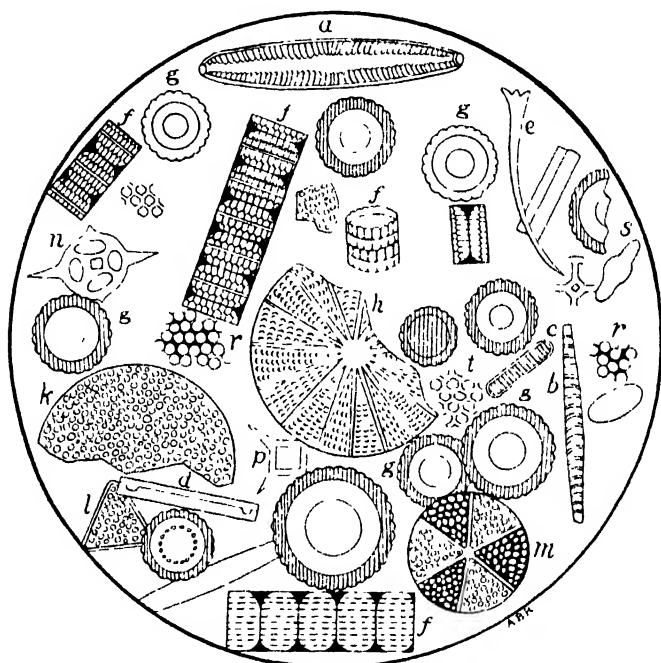


FIG. 47. Infusorial Earth, Richmond, Virginia, U.S.A. (After J. D. Dana.)
 a, *Pinnularia perigrina*; b, c, *Odontidium pinnulatum*; d, *Grammatophora marina*; e, *Spongiolithus appendiculata*; f, *Melosira sulcata*; g, transverse view of f; h, *Actinocyclus Ehrenbergi*; k, *Coscinodiscus apiculatus*; l, *Triceratium obtusum*; m, *Actinopterychus undulatus*; n, *Dictyochoa crux*; p, *Dictyochoa*; r, fragment of *Actinopterychus senarius*; s, *Navicula*; t, fragment of *Coscinodiscus gigas*.

The organisms, as in Barbados Earth, are set in 'a felted mass of interlacing fragments of radiolaria and sponge spicules'. In the case of Diatomite, the principal components are diatom frustules with apparent mineral matter, clay and other micro-organisms. Infusorial Earth is a fine white powder, mainly diatoms, with silica and a little calcite, characterized by its extreme homogeneity. These

plant remains assume spherical, cylindrical, cellular and triangular shapes and usually comprise many different recognizable species. In some examples, a few *polycystines* (siliceous *foraminifera*) occur.

Types. Recent and Tertiary Radiolarian Earths, Barbados, Trinidad, B.W.I.¹; Recent Diatomite, Skye, Aberdeenshire etc., N.B.²; Tertiary Infusorial Earth, Richmond, Virginia, U.S.A.³

References

¹ A. J. Jukes-Browne and J. B. Harrison, *Quart. Journ. Geol. Soc.*, **48**, 1892, p. 174.

² *Mem. Geol. Surv., Spec. Rep. Min. Resources Gt. Brit.*, **5**, 1916, p. 35.

³ J. D. Dana, *Manual of Geology* (American Book Company, New York), 1876, p. 496, Fig. 882.

General Reference

N. Goodwin, Bibliography of Diatomaceous Earth, *Chem. Met. Eng.*, **23**, 1920, p. 1158.

(B3) FERRUGINOUS DEPOSITS. Research on sedimentary iron-ores, more especially the bedded iron-ores of England and Wales by A. F. Hallimond*, has shown conclusively the dominating influence of chemical reaction and precipitation in the formation of these deposits. For this reason these rocks are more logically considered under the heading of chemically-formed deposits (Group C, p. 275). On the other hand, due recognition of the important part played by bacteria in the chemical processes and the belief in certain cases that iron deposits are due directly to organic origin of this kind, make it advisable to retain a place in the present scheme under the heading of organically-formed deposits, more especially in view of the fact that considerable research is still in progress to determine the precise nature of the organic reactions known to take place. This is but another instance of the difficulty of fitting all sedimentary rock-types into 'water-tight' compartments, not that the author admits either the practice or desirability of so doing in this book.

A. F. Hallimond†, writing on this subject, says, 'The role of the "iron bacteria" in the formation of the iron ores has lately received much attention, but it seems likely that this small group represents only a fraction of the organisms concerned and that the action of the ordinary types of bacteria is of no less significance and of far wider extent . . . the crystalline nature of the rocks as seen in the micro-section rarely offers the suggestion of anything but a purely inorganic reaction. Such a system is, nevertheless, not at variance with the theory of bacterial action. . . . Iron and other inorganic materials may not play a part in the structure of the organism itself, but they will be affected in various ways according to the

* *Mem. Geol. Surv., Spec. Rep. Min. Resources Gt. Brit.*, **29**, 1925.

† *Op. cit.*, p. 14.

products yielded by the organism, so that, for example, the reduction of ferric oxide and the production of carbon dioxide in quantity may depend entirely on the existence of suitable organisms which need not themselves be iron-secreting. The insoluble compounds of the inorganic materials are, however, very limited in number, so that the ores precipitated cannot present a chemical or mineralogical variety at all comparable with the variety of organisms that may be concerned. In this way it seems possible to reconcile the uniformity of the ironstones with the probability that their formation is partly or wholly conditioned by bacteria.'

Thus, Lake-ore or Bog Iron-ore has been attributed by more than one writer directly to organic process, decomposition of vegetable matter and influence of bacteria and has been discussed under this heading. In this book both are described in conjunction with other sedimentary ferruginous deposits in the category of chemically-formed rocks, for reasons above stated.

(B4) CARBONACEOUS DEPOSITS. This somewhat heterogeneous group comprises the naturally occurring solid hydrocarbons, the inherent variations and abundant transitional types of which render them difficult to bring within the limits of a few main types. All agree, however, in fundamental biological origin, in which vegetable matter has played a significant part. The pure petrology of these rocks has been conspicuously neglected, save in one or two instances referred to in the sequel. They are none the less all susceptible to petrographical analysis along precise lines of investigation, though much depends on the production of the necessary thin sections, notoriously difficult to achieve in many of the types, *e.g.* coals, asphalts.

No attempt is made here to consider every possible carbonaceous rock encountered in the technology: that would be considerably beyond the scope of this volume. Nor is the fact lost sight of that, in the case of the coals and allied rocks, ultimate structural analysis rests largely on competent palaeobotanical knowledge, again outside the province of this book. On the other hand, carbonaceous rocks have a very definite petrology, at once significant as a study of their mineral composition and of certain factors concerning their genesis. Recent tendencies have shown a desire existing among many geologists to bring such petrology up-to-date and it is hoped that what follows in this connexion will help to clear the ground for further research.

The following subdivisions of the carbonaceous rocks may be made as a provisional basis of discussion:

(B4.1) Peat (p. 262).

(B4.2) Lignite (p. 263).

(B4.3) Coal and Anthracite (p. 264).

(B4.4) Cannel and Torbanite (p. 267).

(B4.5) Oil Shale (p. 268).

(B4.6) Asphalt, Asphaltic Bitumen and Bituminous Impregnations (p. 269).

(B4.1) PEAT

Def. Accumulated vegetable matter composed chiefly of moss and bog plants and forming extensive superficial deposits in suitable moist environments.

Lith. Partially carbonized vegetable matter in which much of the latter is still recognizable in the form of plant roots, stems, fibres, etc. There is often, however, a fine, earthy, clay-like matrix, very homogeneous in character and only decipherable under the microscope. Colour varies from dark brown to black, while texture and degree of consolidation are very variable. A certain amount of mineral-matter in the form of sand is often visible to the naked eye. Hill or 'upland' peat, as it is termed, differs in outward characters from fen-peat, the latter being essentially swamp-muck. Upland peat is more fibrous and spongy and contains much *sphagnum* and other mosses, while tree-trunks and branches may be embedded in it. Fen-peat is more homogeneous, darker in colour and is composed largely of amphibious swamp-plants, e.g. sedge, rushes, etc. A very crude 'stratification' is sometimes apparent in large samples.

Text. Coarse, fibrous, earthy; often compact and clay-like.

Shape. Mineral particles A.

Min. Comp. Mineral particles are chiefly quartz, iron-ores and the more stable accessory species common to neighbouring rocks. In the most compact types, inorganic matter may be less than 3%.

Mech. Comp. Grade-size of mineral particles variable, but often of the sand-grade.

Micro. Peat varies microscopically according to the depth below the uppermost layers from which samples are taken. The superficial material is incoherent when dry and any inorganic matter is easily washed out with water. The rest consists of modern plant material, much fibrous tissue, rootlets, etc. With greater depth, samples become more compact and change in character, incipient carbonization also being apparent. Relieved of its water, this material is made up largely of a blackish-brown, inert, clay-like substance (humus), a restricted amount of plant-remains and 'sand', recognizable from scattered quartz grains (with polarized light). For the most part this form of peat is structureless, the ingredients lying haphazardly, except in the lowest layers, when some degree of parallelism (bedding) may be observed. The inorganic matter is best studied by segregating it from the mass of the rock (Vol. I, Ch. III, p. 125).

Types. Upland peat from the Pennine Hills, England, and from the Grampians, Scotland; Lowland or Fenland peat from Cambridgeshire, etc.¹

Reference

¹ E. A. N. Arber, *The Natural History of Coal* (University Press, Cambridge), 1912, ch. iv, and refs. cited.

General References

F. W. Clarke, Data of Geochemistry, *U.S. Geol. Surv., Bull.* 770, 1924, p. 760 and refs. cited.

G. W. Tyrrell, *Principles of Petrology* (Methuen, London), 1926, p. 243.

(B4.2) LIGNITE

[Pl. 52A, between pp. 240–241]

Def. Lignite is a group term denoting types of coal intermediate between peat and bituminous coal, containing over 20% of water and usually associated with post-Carboniferous (especially Tertiary) deposits.

Lith. The term 'lignite' covers a number of different substances which, in so far as carbonization is concerned, fall midway between peat and coal (bituminous). Examples are lignite proper, brown coal, pitch and glance coal, jet, etc. Such rocks occur in the geologically younger deposits, chiefly Mesozoic and Tertiary, in contradistinction to the bituminous coals of Palaeozoic age. The rock is normally compact, with a dull black or brown lustre, these also being the characteristic colours. Composition and external features vary widely. In thin seams it is often intersected with fine vertical or oblique cracks and splinters readily. More massive material breaks with conchoidal fracture. Plant remains seldom recognizable megascopically. Clusters and aggregates of pyrite common.

Text. Uniform, fine, smooth; in some varieties earthy.

Shape. Mineral particles usually A.

Min. Comp. Quartz, iron-ores (especially pyrite), zircon and other occasional accessories. In some of the Bovey Tracey lignites (Devonshire) detrital minerals derived from the Dartmoor granite and associated rocks have been isolated.

Mech. Comp. Mineral particles variable, but on the whole of fine (silt) grade.

Micro. Thin sections of lignite exhibit much brown, translucent matter for the most part optically inert, though faint birefringent reaction in patches is sometimes discernible. Traces of vegetable structure are frequently noted. Pyrite and limonite staining are common features. The average section tends to be thick and opaque in the centre, though the edges are frequently very thin and this facilitates observations. Gypsum and calcite have both been observed in these rocks. In many examples there is noted a rough parallelism, sometimes distinct lamination, of the chief organic ingredients. The presence of veins and pockets filled with secondary mineral is not uncommon. The inorganic matter is best studied separately as a segregation from the main mass of the rock, by digesting it with suitable solvent (Vol. I, Ch. III, p. 125).

Types. Upper Lias, Whitby, Yorkshire, 'Jet', homogeneous, coal-black substance, with resinous lustre and conchoidal fracture, often

showing coniferous wood structures under the microscope¹; Wealden (Wadhurst Clay), Sussex, lignite seams with pyrite, calcite²; Fairlight Clay, lignite associated with siderite, etc.³; Upper Oligocene, Bovey Tracey, Devonshire, typical lignite with *Sequoia* wood, fronds of *Osmunda lignitum*, leaves and seeds of various plants, and conspicuous mineral matter⁴.

References

¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources Gt. Brit.*, 7, 1918, p. 22.

^{2, 3} Author's observations.

⁴ *Op. cit.*, p. 1; also A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, p. 578.

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F. W. Clarke, *Data of Geochemistry, U.S. Geol. Surv., Bull. 770*, 1924, p. 763, and refs. cited.

(B4.3) COAL AND ANTHRACITE

[Pl. 52B, C, between pp. 240–241]

Def.s. Coal is a group term denoting black carbonaceous deposits formed from accumulation of vegetable matter subsequently carbonized and consolidated under normal diagenetic conditions. Anthracite is a variety of coal containing less than 10% volatile matter.

Lith. Under this heading are considered the so-called bituminous coals and anthracite. Both imply, for the most part, considerable geological age (Palaeozoic) for their achievement. In composition and degree of carbonization, bituminous coal may be said to lie between lignite on the one hand and anthracite on the other; but the term cannot be sharply defined, as some coals decidedly 'overlap' the lignite types, while transitions to anthracite are common. Anthracite as defined above is essentially a variety of coal containing less than 10% of volatile matter and over 90% of carbon. Lithologically, bituminous (or humic) coal presents the appearance of a well stratified, carbonized mass of vegetable matter, some of it discernible as such, much of it compact, homogeneous and void of megascopic structure. Bedding may be thin or thick; sometimes exceedingly fine laminae are developed. Both texture and lustre are notable, alternating dull and bright bands being characteristic. Coal is always well jointed, yielding roughly rectangular blocks. The presence of pyrite along the bedding planes, on joint-surfaces or in pockets, is common. Anthracite is much harder than ordinary coal, has a somewhat metallic lustre, does not soil the hands and breaks with an irregular, conchoidal fracture.

Considerable difference of opinion exists regarding the nature of the materials composing the coal-substance. As some of these are given particular names and can be recognized megascopically, they may conveniently be mentioned here, though to some extent this anticipates remarks under 'microscopical observations'. The '*Fusain*'

component is the soft, powdery, charcoal-like material detected along some of the bedding planes. In contrast to this is the compact '*Bright Coal*' and '*Dull or Matt Coal*'; to the latter M. C. Stopes has given the name '*Durain*'. The bright coal (sometimes known as '*Glance Coal*') much resembles jet. The dull coal is grey-black, lustreless and rough. There are, further, two varieties of bright coal, '*Clarain*' and '*Vitrain*'; the former exhibits smooth surface and glossy lustre, with fine lamination; it also shows intercalations of durain. Vitrain, on the other hand, is homogeneous, with brilliant lustre, conchoidal fracture, presenting cleancut boundaries to the associated substances; it is supposed to represent 'hardened colloidal carbonaceous jelly resulting from complete decomposition of plant matter'².

C. S. Fox has had occasion to examine these coal substances in really thin sections under the microscope and has reached certain conclusions which differ in fundamental respects from the views just summarized³. These are more appropriately discussed below.

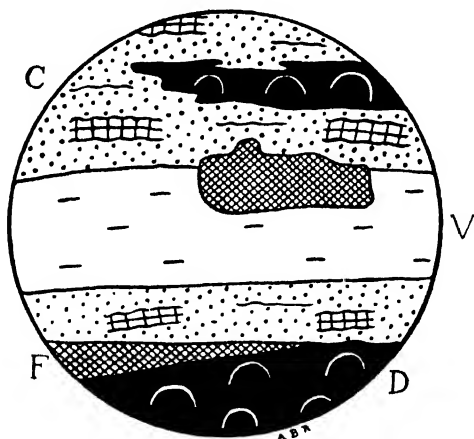


FIG. 48. Coal Constituents; C, clarain; D, durain; F, fusian; V, vitrain. (After M. C. Stopes, *Proc. Roy. Soc., London*, B. 90, 1917-19, p. 483.)

Text. Variable; fine and compact, to coarse, powdery, earthy in coal; fine, smooth, resinous in anthracite.

Shape. Mineral particles A. Isolated particles of coal-substance also A.

Min. Comp. Al. Quartz, tourmaline, garnet, zircon, rutile, metallic ores etc.; more rarely sulphides and native elements (p. 126).

Au. Calcite, siderite, pyrite, limonite, silica, ankerite⁴ etc., in addition to the various forms of carbonaceous matter.

Mech. Comp. Detrital constituents usually of fine grade.

Micro. The essential factor to the study of coal, of whatever kind, is a really thin, translucent, if not transparent section; this requires considerable skill to prepare and, in point of fact, the best sections

available have so far been produced by one laboratory whose method has not been divulged. C. S. Fox, working on slides from this laboratory, has examined the so-called substances clarain, vitrain, durain and fusain derived from certain British coals (both in parallel and transverse sections), and writes as follows:⁵ 'Except for the slides of so-called fusain, which obviously contain much inorganic matter—pyrite, calcite and siderite—as well as what appears to be free carbon, the matrix, where thin enough to be translucent, is composed of the madder-red substance. In the sections cut vertical to the laminae this substance shows very faint pleochroism in plane polarized light and decided straight extinction between crossed nicols, and again behaves as though the whole were part of a single crystal'. He also found in all the slides sections of the resinous wall of spores of red or gold colour, with bright, gold, translucent microspores packed in along the laminae. He further says, 'In all the slides cut parallel to the bedding the translucent madder-red material behaves as an isotropic substance in polarized light . . . (with) a doubtful approach to a uniaxial figure'. He believes that the madder-red material is the same in all slides examined and concludes that 'There is no doubt whatsoever that the substance called vitrain is the same as clarain'. 'In short, the coal constituents are: (a) Vitro-clarain or pure bright coal as the chief component; (b) sporangia cases and spores and other resinous bodies as modifying constituents; (c) mineral charcoal or fusain as a peculiar subsidiary constituent, evidently marking a "break" in the normal process of coal accumulation; and (d) the primary inorganic matter of the original plant as well as the secondary inorganic material which has been deposited in the coal, in joints and cracks and other channels for infiltrating waters'. Every student of coal, whether from a palaeobotanical or petrological standpoint, should read this paper carefully. The author's observations serve to confirm much of what that investigator has stated. C. S. Fox does not, however, touch on the detrital constituents of these rocks, which are no less interesting and significant; for methods of study, see Vol. I, Ch. III, p. 125. Finally, the work of A. Stuart may be quoted on South Welsh anthracite; he 'has been able to distinguish bright bands of splendid lustre and structureless character, corresponding to vitrain; black bands of fairly bright coal with waxy lustre, and dark black "charcoal" bands, representing fusain'⁶.

Types. Palaeozoic, Coal Measures, Warwickshire, Lancashire and Yorkshire coalfields, etc.⁷; anthracite from South Wales etc.⁸ (N.B.—C. S. Fox's slides were of coal from Exhall, Warwickshire, and from the Trencherbone coal, Atherton, Lancashire.)

References

- ¹ *Proc. Roy. Soc. London*, B, **90**, 1919, p. 470.
- ² G. W. Tyrrell, *Principles of Petrology* (Methuen, London), 1926, p. 245.
- ³ *Mining Mag.*, **36**, 1927, p. 16.
- ⁴ T. Crook, *Miner. Mag.*, **16**, 1912, p. 219.
- ⁵ *Op. cit.*, p. 20. See also H. B. Milner, *Mining Mag.*, **36**, 1927, p. 93.
- ⁶ *Geol. Mag.*, **61**, 1924, p. 360, quoted from G. W. Tyrrell, *op. cit.*, p. 247.

⁷ A. J. Jukes-Browne, *Stratigraphical Geology* (Stanford, London), 1912, p. 294.

⁸ A. Stuart, *op. cit.*

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D. White and R. Thiessen, *The Origin of Coal*, *U.S. Bur. Mines*, **38**, 1913.

M. C. Stopes and R. V. Wheeler, *Monograph on the Constitution of Coal*, *Dept. Sci. and Indust. Research*, London, 1918.

R. Thiessen, *Journ. Geol.*, **28**, 1920, p. 185. (See also paper by C. S. Fox (above) for review of literature dealing with microscopy of coal.)

F. W. Clarke, *Data of Geochemistry*, *U.S. Geol. Surv., Bull.* **770**, 1924, p. 768 and refs. cited.

R. Potonié, *Einführung in die allgemeine Kohlenpetrographie*, Berlin, 1924.

R. Thiessen and G. C. Sprunk, *Microscopic and Petrographic Studies of Certain American Coals*, *U.S. Bur. of Mines, Tech. Paper* **564**, 1935.

(B4.4) CANNEL AND TORBANITE

[Pl. 52D, between pp. 240-241]

Defs. Cannel is a dull, lustreless variety of coal characterized by a particular conchoidal fracture. It is rich in volatile matter.

Torbanite is technically a variety of oil shale, named originally from Torbane Hill (Midlothian area, Scotland); it has also been described as 'Boghead Cannel' and has been legally defined as 'coal' (see ref. ³ on p. 268).

Lith. The distinction between cannel and torbanite on the one hand, and between torbanite and oil shale (B4.5) on the other, is by no means an easy one to make; practically every gradation exists between them. The essential property of cannel is its dull, lustreless character, conchoidal fracture and ability to burn readily with a bright flame, since it contains considerable amounts of volatile matter. Torbanite is similar in external appearance; it also contains a high percentage of volatile matter, but is characterized by peculiar spore or algal structures (see below). Both cannel and torbanite (to which latter the name '*boghead cannel*' is often given) contain considerable mineral matter; when this exceeds the carbonaceous matter, the rock automatically passes into the category of oil shale. Torbanite is definitely considered to be an oil shale by some authors¹. Bedding may or may not be apparent in these types; usually, if developed at all, it is on a large scale. Jointing is common and both types tend to break into roughly rectangular blocks.

Text. Both cannel and torbanite are close-grained, fine, compact and homogeneous; the former often has a pitch-like texture, the latter is somewhat resinous.

Min. Comp. Little is known as to the nature of the mineral components of these rocks; detrital minerals are few and uninteresting in samples examined by the author. The coal-substance has been regarded by R. Potonié as '*sapropel*', a solidified jelly-like carbonaceous slime.

Micro. Under the microscope, slides of cannel and torbanite exhibit

beautiful vegetable structures, differing considerably from bituminous coals, but showing affinities with the richer types of oil shale. Thin sections of cannel exhibit a number of plant-spores set haphazardly in a translucent, more or less optically inert, structureless mass. Torbanite contains an abundance of yellow, oval bodies considered to be spores by some authorities, *algae* by others. Cannel is stated to be composed largely of the spores of *Lycopods*; torbanite, of gelatinous *algae* known as *Pila* and *Reinshia*; actually the true nature of these organic remains is the subject of considerable controversy. For the rest, both coals indicate the presence of inorganic matter, *e.g.* calcite, pyrite, limonite, quartz, but the substances characteristic of bituminous coals seem to be absent, indicating a totally different origin for cannel and torbanite, or at least a different mother-substance; on this most investigators are agreed, but more research is required before these types can be said to be defined petrologically.

Types. Cannel from the Coal Measures of North Staffordshire, Yorkshire, Flintshire etc.²; Boghead or Torbanite from Torbane Hill, Scotland ('Torbane Hill Mineral, West Lothian')³; 'Tasmanite', Tasmania, 'spore coal'⁴.

References

- ¹ A. Holmes, *Nomenclature of Petrology* (Murby, London), 1920, p. 227.
- ² *Mem. Geol. Surv., Spec. Rep. Min. Resources Gt. Brit.*, 7, 1918, p. 46.
- ³ Oil Shales of the Lothians, *Mem. Geol. Surv.*, 2nd ed., 1912, p. 159; 3rd ed., 1927, pp. 1, 242, etc.; H. R. J. Conacher, *Trans. Geol. Soc. Glasgow*, 16, 1917, p. 164.
- ⁴ R. Potonié, *op. cit. infra*, p. 28.

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- E. A. N. Arber, *Natural History of Coal* (University Press, Cambridge), 1912.
 R. Potonié, *Allgemeine Petrographie der 'Olschiefer' und ihrer Verwandten*, Berlin, 1928.
 R. Thiessen, Origin of Boghead Coals, *U.S. Geol. Surv., Prof. Paper* 132, 1925.

(B4.5) OIL SHALE

[P1. 53A-F, between pp. 256-257]

Def. A particular type of shale, of black or brown colour, containing a substance known as 'kerogen', which yields crude petroleum on destructive distillation.

Lith. Oil shale, if the exceedingly rich types approximating cannel and torbanite be excluded, normally combines the essentials of ordinary sedimentary shale (A3.9, p. 240) plus a varying amount of carbonaceous matter which, on destructive distillation, yields a form of petroleum. It differs considerably in megascopic characters from either cannel or torbanite. Usually black, brown or greyish-brown in colour; distinct lamination, often finely developed. Many varieties have a leathery appearance and when cut with a knife peel in the form of curved flakes, which may burn with a luminous flame.

Text. Fine, smooth, often polished; some varieties resinous.

Shape. Detrital particles A to SA.

Min. Comp. Al. As for shale (A3.9, p. 240).

Au. Carbonaceous matter of distinctive character (see below) in addition to carbonate of lime, silica, limonite and clay-substance. Part of the carbonaceous matter from which oil is distilled is known as 'kerogen'.

Micro. Oil shale should be studied petrologically in the same way as ordinary shale, *i.e.* by parallel and transverse sections. Under the microscope the essentially laminated feature is seldom in doubt, while quartz, iron-ores and secondary minerals such as limonite and calcite, also pyrite, are easily diagnosed. The organic matter, however, presents a more difficult problem. According to some observers there are four distinct types of material: the 'ulmic' binder or ground-mass, spore and pollen exines, cuticles and cuticular secretions, and *algae*; the latter approximate similar bodies found in spore coals (B4.4). With approach to cannel or boghead types, the organic matter becomes more pronounced and includes fronds, filaments of *algae*, *fungi* fragments, etc. Some measure of parallel orientation of the organic material is observed in these shales, but the inorganic impurities are on the whole irregularly distributed. In some varieties, crystalline calcite occurs as secondary infillings of plant spores or replacing algal structures.

Types. Oil shale from the Lothians, Scotland, type material¹; Kimmeridge oil shale, Dorset, a variable type with calcite, pyrite and a distinctive pyritized crinoid, *Saccocoma*, visible to the naked eye on bedding planes²; Tertiary oil shale from Green River, Utah, with crustacean material, cuticular spores and resins³.

References

¹ Oil Shales of the Lothians, *Mem. Geol. Surv.*, 2nd ed., 1912, and 3rd ed., 1927; H. R. J. Conacher, *Trans. Geol. Soc. Glasgow*, 15, 1917, p. 161.

² *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 7, 1918. (For significance of *Saccocoma*, see *Geol. Surv., Gt. Brit., Summary of Progress*, 1910, p. 62, etc.)

³ W. H. Twenhofel, *Treatise on Sedimentation* (Baillière, Tindall and Cox, London), 1926, p. 297 and refs. cited; also Fig. 32.

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T. Stadnichenko and D. White, *Bull. Amer. Assoc. Pet. Geol.*, 10, 1926, p. 860.
R. Potonié, *Allgemeine Petrographie der 'Olschiefer' und ihrer Verwandten*, Berlin, 1928.

(B4.6) ASPHALT, ASPHALTIC BITUMEN AND BITUMINOUS IMPREGNATIONS

[Fig 49, p. 272, Pl. 54A-F, between pp. 256-257, and Pls. 67-70, between pp. 528-529]

Def's. The nomenclature of asphalt and bitumen is notoriously conflicting. Certain current British Standard definitions are here quoted, but they are based essentially on industrial, not academic, interpretation.

Asphalt. 'A mixture of bitumen with a substantial proportion of inert mineral matter'.

Bitumen. 'A water-proofing and adhesive material which consists of a non-crystalline, solid or viscous mixture of complex hydrocarbons. It softens gradually when heated and is substantially soluble in carbon disulphide. It is obtained either by refinery processes from petroleum or is found in association with mineral matter as a component of naturally occurring asphalt'.

Lake Asphalt. 'An asphalt which, as found in nature, is in a condition of flow or fluidity'.

Natural Rock Asphalt. 'A naturally occurring consolidated calcareous rock impregnated with bitumen exclusively by a natural process'.

Lith. In this category are placed those peculiar forms of solid hydrocarbon ranging from the purest bitumen deposit, to rocks in which only a comparatively small percentage of bitumen occurs as impregnating material. While this course may be conveniently adopted as a basis of petrological description, from chemical and physical standpoints the materials vary widely and can hardly be said to come under any one heading. It will further be obvious that, in the case of low percentage impregnation-types, bitumen-bearing rocks constitute hybrids of mechanically- and organically-formed deposits, which might at first glance seem to justify their segregation from the purely carbonaceous deposits; but with types in which the organic material may vary from anything up to 99%, it is difficult to draw any sharp line of division and as the majority is indeed highly carbonaceous, there is little reason for defining a separate hybrid group. At the outset it is emphasized from the above definitions that the term 'bitumen' is really a group-name to include most of the naturally occurring hydrocarbons, of which 'asphalt' is a particular solid or semi-solid variety; 'bitumen' is, however, often used colloquially as synonymous with 'asphalt', hence much of the prevalent confusion in nomenclature.

Megascopically, pure, native bitumen is characterized by a black colour, glossy appearance, definite fracture and brittle tendencies; with the approach to semi-solid forms, fracture and brittle tendencies are obliterated, also the colour often changes to shades of dark brown; where the bitumen occurs as an impregnation, *e.g.* in limestones or sandstones, it tends to be very finely disseminated and to play much the same role as an infiltrating mineral solution.

The following different types of these rocks may be recognized: native asphalt, containing less than 10% of mineral matter; native asphalt occurring in all proportions as impregnating material or sediments; so-called 'asphaltites' which include gilsonite, glance pitch and grahamite (the 'manjak' of Barbados belongs here); and asphaltic pyrobitumens, including albertite, claterite, etc. which, with increasing mineral matter, pass into asphaltic shales, finally bridging the gap between asphalt as such and oil shales.

Text. Mineral particles when excessive may produce a gritty texture, but in the purest forms asphalt is very smooth, homogeneous and pitch-like.

Shape. Detrital particles A to SA.

Min. Comp. Excluding bituminous rocks, the only minerals discernible under the microscope in native asphalts, etc., are stable detrital species normal to the environments concerned. The hydrocarbon behaves as a dense, complex matrix, void of any crystalline properties. Most of the asphaltic limestones ('rock asphalts') from well-known localities, e.g. Seyssel and Pyrimont, St. Jean de Maruéjols (Gard), France; Neuchatel and Val de Travers, Switzerland; Ragusa, Sicily; Scafa, Italy; Voerwohle, Germany, yield restricted though distinctive detrital (heavy) mineral residues.

Micro. The method of studying these rocks depends largely on their nature, purity and degree of solidification. Where it is possible to cut thin sections, these should always be employed; this applies to solid native asphalts and asphaltites, equally to all impregnated rocks. Detrital minerals are best investigated as concentrates segregated by dissolving out the hydrocarbon (Vol. I, Ch. III, p. 127, and Ch. VII, p. 265). [N.B.—In the preparation of the thin section, the greatest care must be taken to avoid heating the material sufficiently to cause it to flux with the mountant, or otherwise to develop artificial structure.] Under the microscope asphalt exhibits a brown translucency where sufficiently thin; but not many optical reactions can be obtained, nor in most cases can any structure in the hydrocarbon be made out. Where mineral matter is present, the quartz grains are easily picked out by polarized light; sometimes incident light observations aid the discrimination of organic and inorganic matter. Many examples of asphalt which, from megascopic observation, seem remarkably pure, are found to contain abundant quartz and other minerals on closer analysis.

The most interesting and profitable research, however, is that of the impregnated rocks where, given a skilfully prepared section, the manner and degree of impregnation of a normal sedimentary rock can be studied. In these cases much depends on the rock itself. With sandstones, the bituminous material is seen to act very much in the nature of a cement, filling voids and mineral-interstices, or where bedding is manifest, 'pushing' its way along the planes, often disrupting the normal relationship of the quartz particles. Sometimes a definite linear distribution of the bitumen is noted, in other examples, especially in fine-grained sandstones and siltstones, it more or less saturates the rock. Porosity plays an important part and where this is seen to vary, producing a 'tight' sand, impregnation often stops abruptly. Impoverishment of the hydrocarbon causes it to appear in patches throughout the rock.

In limestones the manner of impregnation is largely determined by the nature of the organic components and the degree of crystallization of the matrix. Often the fossil shells are sufficiently filled with mineral matter to avoid further contamination by the hydrocarbon, which is thus forced to confine itself to the matrix or to voids; on the other hand, where mineral infilling of shells or chambers is loose or wanting, or where cracks have been developed through which the original crude petroleum could penetrate, bitumen may be seen to fill not only the interiors, but often fractures and cracks in the shells and

even in calcite crystals. Where fine-grained calcareo-argillaceous rocks are involved, *e.g.* marl, 'patterning' of the bituminous material is very characteristic, due to the irregular porosity and permeability of the rock towards the hydrocarbon. In these cases it will often adhere to those planes or parts of the marl in which some degree of secondary crystallization of the calcareous mud is apparent; where, however, it has been able to saturate the rock-particles, the whole specimen shows discoloration and high power magnification reveals thin films of asphalt coating the constituent particles. With excess of the hydrocarbon, seams of almost pure asphaltic bitumen tend to alternate with non-impregnated rock and a definitely banded structure is seen. The existence of jointing in such rocks determines 'leakage' of the hydrocarbon from one layer to another and sometimes the spread of detrital grains which are thus locally transported: this phenomenon constitutes a very pretty study under the microscope.

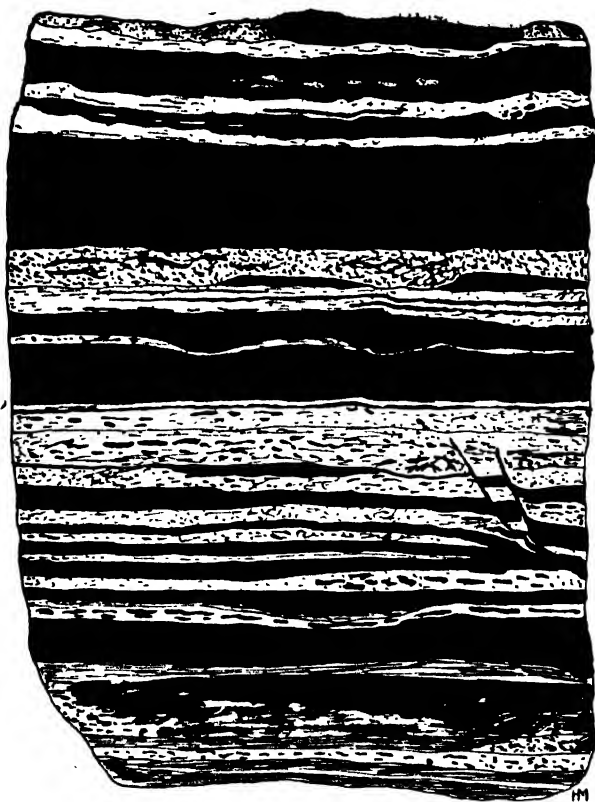


FIG. 49. Impregnated (Asphaltic) Limestone Dept. of Gard, France (half natural size).

Types. Asphalt from the Bermudez 'Pitch Lake', Venezuela, with just over 3% mineral matter¹; asphalt from the 'Pitch Lake', Trinidad, B.W.I., with 27% mineral matter (crude material)²; Glance Pitch or 'Manjak' from Barbados³; asphaltic impregnated sandstone, Péchelbronn, Alsace⁴; asphaltic limestone, Val de Travers, W. of Neuchâtel Lake, Switzerland, up to 10% normal impregnation⁵; impregnated limestone, marl, sandstone and shale, St. Jean de Maruéjols, Department of Gard, France, between 5% and 6%⁶.

References

- ¹ H. Abraham, *Asphalts and Allied Substances*, 5th ed. (D. Van Nostrand, New York), 1945, p. 159.
- ² *Ibid.*, p. 195; also A. W. Attwooll and D. C. Broome, *Trinidad Lake Asphalt*, 2nd ed. (The Baynard Press, London), 1954.
- ³ H. Abraham, *op. cit.*, p. 261; also R. J. Morgan, *Chem. Eng. Min. Rev.* **13**, 1921, p. 348.
- ⁴ P. de Chambrier, *Historique de Péchelbronn*, Paris, 1919.
- ⁵ M. Frey, Die Asphaltlagerstätten im Schweizerischen Juragebirge mit besonderer Berücksichtigung des val de Travers, *Bert. Geol. Schweiz.*, 1922.
- ⁶ M. P. Nicou, *Ann. des Mines*, **10**, 1906, p. 513.

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 H. Abraham, *op. cit.*

(B5) PHOSPHATIC DEPOSITS. These comprise the phosphatic rocks of organic origin as distinct from mineral apatite deposits and although sporadically developed on a large scale in different parts of the world, they are comparatively unimportant as petrological studies. The group includes phosphorite, the primary metasomatic form of phosphate (hydro- or fluo-calcium carbonophosphate); guano, a friable or earthy type derived from the excrement of seabirds, etc.; the coprolites or fossil excreta of fishes, reptiles and mammals. Closely allied are the bone-breccias of similar composition. Many local varieties of these deposits are known. For present purposes it is unnecessary to split this group up into separate types, and the following general description will suffice. [*Pl.* 55A, B. between pp. 256-257.]

Def. Phosphorite is the name applied to concretionary masses or other types of deposit of calcium phosphate of organic origin.

Lith. Primary, bedded phosphate deposits, e.g. phosphorite, vary considerably in external characters. The pure types are grey, brown or black, the last usually implying presence of hydrocarbon. Recognizable organic remains may or may not be in evidence; these vary from shell-fragments to bones and fish remains, etc. Different structures prevail according to conditions of formation and to some extent with locality; for instance, in the Nigerian deposits W. Russ has

described granular, nodular, fine and coarse vesicular and compact types¹. In some granular examples small, rounded pellets of an amorphous form, collophane (p. 86) may occur, giving the rock a pseudo-oolitic character. The nodular type 'has a conglomeratic appearance derived from the ellipsoids and irregular cylindrical nodules of calcium phosphate'². The vesicular varieties are altered products into which enter phosphates of iron and alumina. Guano, coprolites and the 'bone-phosphate' of the breccias are for the most part amorphous; guano is dry, pulverulent, earthy and friable (under arid conditions) and contains considerable impurity in the form of nitrate, lime carbonate, etc. Coprolites are grey, green or brownish-black in colour; in some cases they are phosphatized matter entirely, in other examples fossil-shell fragments are included. Various phosphatic nodules found in different strata may either be coprolites in the strict sense, or be composed of collophane, calcium carbonate and mineral matter.

Text. Phosphorite: fine, compact, homogeneous, to coarse, earthy vesicular (like pumice); guano is earthy, friable; nodules and coprolites are usually smooth, sometimes 'soapy'; bone-phosphate is rough, powdery, or hard and compact, sometimes coated with secondary crystalline material.

Min. Comp. These phosphates are essentially varieties of calcium phosphate, with or without fluorine, calcium carbonate, iron phosphate aluminium phosphate, etc. Among specific minerals may be mentioned collophane, dahllite and francolite. Associated impurities include quartz, calcite, dolomite, chert, pyrite, marcasite, glauconite, etc.

Micro. These rocks are among the most variable materials to study microscopically; practically no two examples are alike. Except the rarer compact varieties of phosphate rock, most examples have the appearance of 'conglomerates' in which the 'pebbles' are rounded and of varying sizes, set in a matrix which is clear, turbid or iron-stained. For the most part, the larger constituents are phosphate grains, the matrix is a mixture of phosphate, aluminium phosphate, carbonaceous matter and detrital minerals. Fossil-shell and bone-fragments are common. Some of the phosphate is crystalline and gives definite optical reactions; for instance, in some types of granular, amorphous phosphate there is interstitial aluminous phosphate with bluish-grey aggregate birefringence. Much of this granular, amorphous material is probably collophane. Phosphatic nodules, coprolites, etc., are amorphous, but frequently some sort of nucleus is observed in thin section, e.g. shell-fragment, bone, rarely inorganic matter. Phosphate casts of *foraminifera* and structural grains replacing those organisms are often observed. Various stages in phosphatic replacement of limestones occur. In bone-breccias in which phosphate prevails, both bone-fragments and matrix may be of calcium phosphate, but usually some degree of secondary alteration is noted, with the production of iron phosphate, calcite and silica.

¹ *Geol. Surv. Nigeria, Bull. 7, 1924, p. 11.*

² *Op. cit.*, p. 12.

Types. Upper Cretaceous (Cambridge Greensand), Cambridgeshire, phosphatized fossils, phosphate nodules, etc.¹; Lower Chalk, Cambridgeshire, etc., calcareo-phosphatic nodules of green colour, brown-yellow inside²; phosphate rock, Abeokuta Province, Nigeria, with iron and aluminium phosphates, etc.³; guano deposits of Peru, Christmas Island (Indian Ocean), Navassa Island (Caribbean) etc.⁴; Suffolk Box-stones⁵.

References

¹ F. R. C. Reed, *Geology of Cambridgeshire* (University Press, Cambridge), 1897, p. 100.

² *Ibid.*, p. 127.

³ W. Russ, *op. cit.* (N.B.—This work contains some excellent photomicrographs of phosphate rocks.)

⁴ W. H. Twenhofel, *Treatise on Sedimentation* (Baillière, Tindall and Cox, London), 1926, p. 400.

⁵ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 253.

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F. W. Clarke, Data of Geochemistry, *U.S. Geol. Surv., Bull.* **770**, 1924, p. 523.

A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, **29**, 1925, p. 35.

J. H. C. Martens, Sand, etc., Florida, *Florida State Geol. Surv., 19th Ann. Rep.*, 1928, p. 33 (p. 43 for collophane).

(C) CHEMICAL ORIGIN

This group comprises all inorganic deposits dependent for their formation on precipitation from solution, or on some definite chemical replacement of a pre-existing mineral by another mineral of different composition, the latter process usually referred to as 'metasomatic' change or 'metasomatism'. On account of the obvious influence of organic agency in many geochemical reactions and the constant overlap between organically- and chemically-formed rocks in many instances, the present group is admittedly to that extent artificial. The example already discussed (p. 260) is that of the ferruginous deposits, deliberately relegated to this chemical group notwithstanding the admitted influence of bacterial organisms in their formation.

On the other hand, a majority of rocks falling naturally into this category is clearly inorganic, *e.g.* travertine, calc-sinter, gypsum, anhydrite, rock-salt, etc.; this is a sufficient justification for retaining a division which shall include deposits of such definite chemical

origin and which further lends itself to internal rearrangement of types on the logical basis of chemical composition.

The real distinction between organic and chemical deposits lies in direct or indirect contribution: the former are primarily concerned with accumulation of actual organic substance; the latter may and often do imply organic agency or influence in their achievement, but the actual organisms concerned (or their remains) may not be manifest; in fact it is rarely so in these rocks.

The study of chemically-formed deposits is valuable from many points of view; their petrology (possibly 'mineralogy' would be the more accurate term in most cases) is distinctive and interesting; their stratigraphical occurrences are always an inspiration of problems of genesis and relationship to their associated rocks; their significance in illustrating the principles of cementation of incoherent sediment—the authigenic factor—cannot be overlooked; while to petroleum geologists in particular, such materials as rock-salt, gypsum and anhydrite are of vital importance in many oilfields.

For these and other reasons, chemically-formed deposits invite careful study and the same diligent use of the microscope as is accorded to more complex rock-types.

Following the scheme of sub-classification adopted hitherto, the four main divisions are:

(C1) CALCAREOUS (p. 276).

(C2) FERRUGINOUS (p. 278).

(C3) SILICEOUS (p. 281).

(C4) SALINE (p. 282).

(C1) CALCAREOUS DEPOSITS OF CHEMICAL ORIGIN. This division, relieved of those carbonate developments in which organic influence has clearly operated (dolomitic limestone, oolitic and pisolitic structures, group B), though chemical action in each case has undoubtedly taken place, may be said to be sufficiently distinctive. It includes such deposits as travertine or calc-sinter, stalactite and stalagmite growths, dolomite (in part). In connexion with the latter, much difference of opinion exists as to whether this substance can originate *per se* as a direct result of chemical precipitation from solution, many writers claiming the essential action of magnesia-secreting organisms as instrumental to its formation. The author agrees with those who maintain that the mineral can be generated independently from solution. For instance, dolomite occurs in association with rock-salt, gypsum, anhydrite, etc., in the Trias of Germany, in which development

it does not in the least suggest replacement of an original limestone. These deposits may be subdivided as follows:

(C1.1) Calcium Carbonate: Calcite (p. 277).

(C2.2) Dolomite (in part) (p. 277).

(C1.1) CALCIUM CARBONATE: CALCITE

(See also B1.1, p. 245)

Lith. This subdivision includes the following variable examples: travertine, calc-sinter, calc-tufa, stalactite and stalagmite growths; the first three are practically identical, consisting of accumulations of calcium carbonate possessing cellular, concretionary, compact, or earthy and porous tendencies. Stalactites are the pendant growths of calcium carbonate from the roofs of caves, etc.; stalagmites the corresponding accumulations on the floors of such recesses. 'Onyx Marble', a misnomer, is a well-banded variety of stalagmitic carbonate and belongs here. In the case of travertine, etc., deposition is often quite irregular, producing encrustations and earthy accumulations rather than well organized structures, the characteristic of stalactites and stalagmites, where some development of concentric growth is always apparent when the specimen is split transversely. Colour varies from white, yellow to brown.

Text. Compact to earthy, friable.

Min. Comp. Essentially calcium carbonate, but often with impurities such as iron carbonate, limonite, silica, hydrocarbons, etc.

Micro. The crystalline nature of these rocks is seldom in doubt when tested under the microscope with polarized light. All the characteristic properties of calcite (p. 67) are observed, while the presence of impurities is easily detected. The concentric growth-layers of the stalactites, etc., are often picked out with impurity, e.g. limonite, while subsidiary radial structures may be observed. In the tufas, some proportion of the mineral is powdery and appears to be amorphous; usually no special structure is apparent unless encrustation about some particular nucleus has taken place uniformly.

Types. Carboniferous Limestone of Derbyshire, etc., for all these types of carbonate.

General References

V. C. Allison, *Journ. Geol.*, **31**, 1923, p. 105.

W. H. Twenhofel, *Treatise on Sedimentation* (Baillière, Tindall and Cox, London), 1932, p. 324.

(C1.2) DOLOMITE (in part)

(See also B1.2, p. 250)

Lith. Dolomite occurring as the mineral (not as a partial replacement of limestone) and in intimate association with other inorganic deposits, is an interesting development. In its massive form it constitutes

dolomite rock, a white, grey, green, brown, sometimes pinkish, crudely stratified deposit, often with a somewhat pearly lustre. Brown staining is mainly due to ferrous carbonate, other prominent colouring may be due to manganese compounds. Usually dolomite is close-grained, uniform and difficult to distinguish from limestone except by acid test; on the other hand, in veins or cavities (the latter very common in some examples), characteristic curvilinear crystals, resulting in 'saddle-shaped' aggregates, may be observed, when the mineral is at once easily recognized.

Text. Medium, compact, sometimes friable.

Min. Comp. Essentially carbonate of calcium and magnesium, but with impurities of iron, sometimes manganese; often intimately associated with gypsum, barite, silica, more rarely celestite.

Micro. Under the microscope the simple rhombs of dolomite are, if developed, very characteristic; alternatively, somewhat rectangular forms as constituents of aggregates may be displayed. Where individual crystallization is obliterated by interferent mass-precipitation, a mosaic of irregular grains, almost indistinguishable from calcite, results; in such cases only a chemical test yields positive diagnosis (p. 68). In field-association with gypsum, anhydrite, rock-salt, etc., these minerals may be looked for in the slide and are usually apparent to a greater or lesser extent, especially in joint-channels or cavities. A complete absence of organisms or organic structures is one of the differentiating features between dolomite and dolomitic limestone, though where the latter forms part of the series, separation of the two types is often an exceedingly difficult matter.

Types. Trias, Keuper Marls, Charnwood, Leicestershire, 'quartzose dolomite', compact, granular, blue-grey crystalline rock composed of perfect rhombs of dolomite associated with quartz, aluminous silicate and barite¹; other occurrences from the same formation show perfect rhombs of dolomite²; Raibl Beds, Tyrol, dolomite associated with gypsum³.

References

¹ T. O. Bosworth, Keuper Marls around Charnwood, *Leicester Lit. and Phil. Soc.*, 1912, pp. 54, 82, 84, 108.

² C. G. Cullis, *Rep. Brit. Assoc., Adv. Sci.*, Leicester, 1907, p. 506.

³ M. M. Ogilvie, *Quart. Journ. Geol. Soc.*, **49**, 1893, p. 1.

General References

F. M. Van Tuyl, *Iowa Geol. Surv.*, **25**, 1914, p. 262.

Mem. Geol. Surv., Spec. Rep. Min. Resources Gt. Brit., **6**, 1918, p. 190.

F. W. Clarke, Data of Geochemistry, *U.S. Geol. Surv., Bull.* **770**, 1924, p. 565.

(C2) FERRUGINOUS DEPOSITS (see also Group B3, p. 260). Prevalent ideas with regard to the nature and origin of ferruginous deposits have been considerably clarified by A. F. Hallimond, who has investigated the bedded iron-ores of England and Wales, to which reference has already been made elsewhere*. Apart from

* *Mem. Geol. Surv., Spec. Rep. Min. Resources Gt. Brit.*, **29**, 1925.

the action of *bacteria* or *algae* in instigating or influencing certain chemical reactions from which these rocks result, the essentially inorganic character of these deposits is now generally admitted, even to the extent of denying the probability of oolitic ironstones having been derived by metasomatic process from oolitic limestones. For present purposes it will suffice to recognize two contrasted occurrences.

(C2.1) Bedded Iron-ores (p. 279).

(C2.2) Bog Iron-ore (p. 281).

(C2.1) BEDDED IRON-ORES

[Pl. 55 C-F between pp. 256-257]

Lith. A. F. Hallimond divides the bedded iron-ores into two principal groups, the ferrous and the ferric ores; the former are the chamosite and chamosite-siderite mudstones, non-chamositic siderite mudstones, and siderite limestones; the latter include the ferric chamosite oolites, the limonite oolites, primary hematites and glauconite rocks. The mudstones correspond to the older terms 'clay ironstone' or 'black-band ironstone' of the text books. Megascopically the chamosite and chamosite-siderite mudstones vary greatly; the colour is green or brown; oolitic developments and compact mudstone alternating; organic remains and markings common. The siderite mudstones are on the whole darker in colour, of finer texture, nodular, or in thin beds; they resemble 'cement-stones'. Closely allied to them are the sphaerosiderite rocks, in which spherulitic grains of the mineral are embedded in clay (p. 177). The sideritic limestones differ from the preceding types in consisting of aggregates of shell-fragments cemented with calcite and siderite. Of the ferric ores, the ferric chamosite oolites vary from black to red and brown oolite and pisolitic mudstones, often highly magnetic, with conspicuous bedding and limonite cement; occasionally pyrite in nests. The limonite oolites are composed mainly of oolites of that mineral, not of chamosite as in previous types; they may be closely or sparsely packed, in the latter case the matrix of sandstone or mudstone is usually fine and homogeneous except where organic fragments are common; colour, grey, brown, reddish-brown. The primary hematites include turgite or hematite occurring as pebbly or nodular beds, or in brick-red massive varieties, etc. The glauconite rocks include ironstones in which, as a result of weathering of sands containing that mineral in abundance, iron is concentrated mainly as limonite, though in some cases with a considerable amount of siderite; there is often a clay matrix, while the development of limonitic 'boxstones' is characteristic; this material is in the nature of an 'iron pan'.

Text. Variable, from fine to medium grain in the mudstone facies, coarse to earthy in the oolitic developments.

Shape. Detrital particles SA.

Min. Comp. Al. Quartz, iron-ores and miscellaneous accessory minerals.

Au. (including chemical precipitates), chamosite, siderite, dolomite, ferric oxide, magnetite, pyrite, glauconite, clay-substance, calcite, limonite, phosphates (collophane), etc.

Mech. Comp. In the siderite mudstones, ooliths 1/60 in. in diameter; in average cases siderite crystals are about 0.02 mm. in diameter; detrital grains mainly of the silt grade.

Micro. In these rocks the ooliths are usually of chamosite, one of the chlorite group of minerals and they may or may not contain siderite in rhombs or irregular grains. Siderite ooliths are much less common; these are set in a fine chamosite-mud ground-mass, often rich in siderite in rhombs or crystal-bunches. The chamosite ground-mass is green to brown in colour. Quartz, dolomite and accessory minerals are scattered throughout the rock. In the mudstones the ground-mass may consist of quartz, feldspar, mica and clay-substance, with or without chamosite. A characteristic feature of many of the mudstones is the abundance of fossil-shell fragments often replaced by rhombs of siderite; other organic remains include fish-teeth, casts of boring worms, plant debris, etc. When sphaerosiderite occurs, the spherulites are scattered in a clay-matrix; the former 'are built up of long narrow fibrous crystals with straight extinction, radiating from the centre and often terminating in an irregular angular outline; sometimes the component crystals are fewer and broader. The ground-mass is generally of fireclay type, and is sometimes present in so small an amount that the spherules meet, forming polygonal cells. When quartz, etc., is present in the ground-mass, some of the coarser grains are often included in the spherules, an indication that these grew within the clay'. The sideritic limestones exhibit siderization in all stages from cementing medium to complete replacement of calcite (metasomatism). In the limonite ooliths, the matrix consists of weakly birefringent clay-substance (? altered chamosite) with siderite, dolomite, quartz, etc.; the ooliths themselves are brown, translucent, and with radial-fibrous and concentric structure. Sometimes each grain is coated with an isotropic film of chamosite. In the glauconitic varieties, this mineral occurs conspicuously; the ooliths are of limonite showing concentric structure, set in a brown sideritic cement which also shows alteration to limonite.

Types. Middle Lias, Cleveland Ironstone, Yorkshire, example of chamosite mudstone and chamosite-siderite mudstone; also oolitic Cleveland Ironstone; Wealden, siderite mudstone, also sphaerosiderite (Fairlight Clay, Sussex); Lower Cretaceous, Claxby, Ironstone, Lincolnshire, example of limonite oolite; Lower Greensand, Seend, Wiltshire, glauconitic ironstone with limonite boxes, etc.; Abbotsbury Iron-ore, Dorset, and Westbury Ironstone (Corallian), Wiltshire, both examples of limonite oolites*.

* A. F. Hallimond, *op. cit.* (N.B. - This work so far supersedes pre-existing accounts of these particular rocks as to render further references superfluous, though many will be found therein as footnotes where appropriate.)

Reference

¹ A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 29, 1925, p. 67.

(C2.2) BOG IRON-ORE*

Def. Bog iron-ore denotes an impure ferruginous deposit formed in swampy ground by oxidizing action of atmospheric or bacterial agency.

Lith. In brittle flakes, thin beds, aggregates or as filmy matter on water-surface; material usually soft, porous and of brown colour. Clay is usually associated with the solid bog-ore, in fact often underlies it; plant remains are common.

Text. Fine, smooth, to earthy and friable.

Min. Comp. Limonite, siderite, clay-substance, with (locally) iron silicate, iron sulphate, vivianite, 'wad' or bog manganese, humus, etc.

Micro. In thin section, the solid iron-ore exhibits a brown to red colour, usually of fairly homogeneous material, much of which is optically inert, though easily studied by means of reflected light. Siderite when present is detected by its characteristic twinkling with the polarizer. Vivianite is of comparatively rare occurrence and is suggested by bluish-green or dark blue prismatic crystals. Organic structures are very conspicuous, normally consisting of rootlets, twigs, leaves, sometimes seeds, frequently replaced by limonite.

Types. Various lacustrine and fluvial iron-ores and 'iron pans'; Scotland, Sweden, etc.

General References

N. S. Shaler, *10th Ann. Rep., U.S. Geol. Surv.*, pt. i, 1890, p. 305.

E. C. Harder, *U.S. Geol. Surv., Prof. Paper* 113, 1919.

R. Beck, quoted by W. H. Twenhofel, *Treatise on Sedimentation* (Baillière, Tindall and Cox, London), 1932, p. 819; also other references therein cited.

(C3) SILICEOUS DEPOSITS. Included under this heading are those rocks owing their existence primarily to inorganic agency, viz. precipitation from solution in which silica in one form or another is prevalent. Here belong siliceous sinter and to a large extent chert and flint. These latter, however, are concerned with recognizable organic remains contributory to their formation, more especially in the case of chert and in the present state of our knowledge it seems desirable to discuss them under the heading of organically-formed rocks, though admittedly the claim of the chemical group is strong. This is another case of difficulty of classification raised by a genesis which contemplates more than one mode of origin. Accordingly chert and flint are described as types of group (B) (p. 244), leaving siliceous sinter as the example of the purely chemical siliceous deposit; even in this case it should be noted that organic agency has on more than one occasion been invoked to account for its formation.

* See also under *Limonite*, p. 138.

(C3.1) SILICEOUS SINTER

Def. Siliceous sinter ('geyserite') is a solution deposit of silica from thermal springs.

Lith. This material is chiefly deposited as earthy encrustations in the vicinity of hot springs or geysers, hence the synonymous term 'geyserite'. It varies in colour from yellow to pink, green, brown, variation being noted with temperature at the time of formation. These colours have been attributed to gelatinous precipitation influenced by certain *algae*, but the mechanism is not perfectly understood. Many examples resemble accumulated concretions, sometimes with a kind of 'onion' structure, at other times having the appearance of 'cauliflower' structure.

Text. Usually earthy, porous and friable.

Min. Comp. Amorphous silica, opal, with impurities of iron, manganese, etc.

Micro. Siliceous sinter examined under the microscope exhibits characteristic 'growth' structure in ordinary transmitted light, but remains for the most part isotropic with polarized light. Few structures which can be termed even micro-organic are observed; certainly *algae* are not conspicuous in the cold, consolidated rock. Colouring matter is finely disseminated and is not attributable to any particular crystalline substance. Fibrous sinter is not uncommon, but individual fibres do not yield optical reactions.

Types. Yellowstone Park, U.S.A.; hot springs of Taupo, New Zealand; geysers of Iceland, etc.

General References

W. H. Weed, *U.S. Geol. Surv., 9th Ann. Rep.*, 1889, p. 613; also *Am. Journ. Sci.*, 37, 1889, p. 351.

G. W. Tyrrell, *Principles of Petrology* (Methuen, London), 1926, p. 223.

R. B. Sosman, *The Properties of Silica* (Chemical Catalogue Company, New York), 1927, p. 796.

W. A. Tarr, *Terminology of the Chemical Siliceous Sediments, Cmttee. on Sedimentation, Nat. Research Council, U.S.A.*, 1936.

(C4) SALINE DEPOSITS. This group covers a variety of chemically-formed rocks characteristic of certain well-defined environments, e.g. lagoons, inland lakes, relic (land-locked) seas, etc. It includes chlorides, sulphates, borates, nitrates, etc., occurring as products of precipitation usually in regular beds or layers, but lacking 'stratification' in the accepted sense. Apart from such developments *per se*, certain of the compounds considered here also occur as replacements of pre-existing rocks, more particularly those of the calcareous group; the sulphates are implied in this connexion. Contrary to usual belief, microscopical examination of these sedimentary salts shows that they are among the most variable rocks found in nature, especially as regards structure; this may be of such a distinctive type as to characterize a particular development over a large area and through a limited thickness of deposit;

thus careful study of structural features, particularly in regard to gypsum and anhydrite occurrences, is a matter of considerable moment in the identification of horizons in thick saline sequences. Such study is, however, much facilitated when chemical analyses of the rocks in question are available; these serve as a guide to the anticipation of closely allied products whose mineralogical characteristics may not be sufficiently obvious to aid their differentiation from the chief constituents. The types chosen to illustrate this group are:

(C4.1) Chlorides (p. 283).

(C4.2) Sulphates (p. 284).

(C4.3) Nitrates and Borates (p. 286).

(C4.1) CHLORIDES

[Pl. 56A, between pp. 256-257]

Lith. The chief examples of this group are rock-salt (halite) and sylvite (potassium chloride); the latter is comparatively rare. Rock-salt occurs either in recognizable crystal-form (halite) with marked cubic cleavage, in granular masses, or as thick, structureless, massive beds. In colour it varies from colourless to white, yellow, red, purple (with increasing impurity). It possesses a strong saline taste and readily dissolves in water. Many specimens exhibit considerable distortion. Sylvite is also an isometric mineral with strong cleavage, though seldom so conspicuous as in the case of rock-salt. It occurs as granular or massive developments, nearly always accompanied by impurities.

Text. Fine, glassy or 'sugary'.

Min. Comp. Halite (NaCl), with many impurities and associated salts, e.g. sulphates, carbonates, clay-substance, silica, etc. Sylvite (KCl), usually with halite, silicates, nitrates, etc.

Micro. Both rock-salt and sylvite are normally isotropic in polarized light, though some examples exhibit anomalous birefringence, probably due to impurities in most cases; strain-phenomena are possible. In ordinary transmitted white light the refractive index of rock-salt is less than Canada balsam, but by a small amount, so that the outlines of the crystals or sections of massive material are not prominent; with sylvite the R.I. is considerably less than that of balsam, with the result that a shagreened surface with bold outlines is characteristic. Colouring matter in both salts is noted as fine disseminations, seldom suggestive of recognizable minerals, except limonite. The cleavage is often well displayed where crystals are in evidence.

Types. Triassic salt deposits, Northwich, Cheshire; Preesall, Lancashire; Staffordshire, etc.¹; rock-salt and sylvite, Stassfurt, Germany².

References

¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, **18**, *Rocksalt and Brine*, 1921.

² F. W. Clarke, Data of Geochemistry, *U.S. Geol. Surv., Bull.* 770, 1924, p. 222.

General Reference

A. W. Grabau, *Principles of Salt Desposition* (McGraw-Hill, New York), 1920.

(C4.2) SULPHATES

[Pl. 56B F, between pp. 256-257, and Pl. 57A-E, between pp. 288-289]

Lith. This group includes gypsum, anhydrite, barite and celestite as the commonest representatives of accumulated 'salt' deposits. As individual minerals they have already received consideration in Ch. I, to which further reference for mineralogical detail should be made. The following notes refer to their occurrence *en masse*. Gypsum normally occurs in massive aggregates of mutually interferent crystals, often decidedly fibrous and with a saccharoidal structure. In colour it is white to pale pink, red or brown, the colouring matter being due to impurity, often to iron compounds or finely divided rock-flour.

Anhydrite also occurs massive, sometimes with distinct fibrous development; crystallization may be very coarse, due to the packing together of crudely rectangular prismatic crystals. The structure is of a schistose character in some examples. Colour white, grey, blue or red. It is much harder than gypsum, this property affording a quick test between the two minerals in hand-specimen.

Barite in sediments is frequently in the form of isolated crystalline masses; it seldom achieves the bedded character of the other sulphates, being essentially a vein-mineral, though exceptionally it may result from the weathering of a barite-bearing limestone, thus assuming the character of a residual deposit. Its usual occurrence is in massive, platy, crystalline aggregates, often with prominent and beautifully formed crystals of characteristic habit (p. 56). Earthy and fibrous varieties occur. Colour varies from white to yellow, brown or red according to degree of purity. This mineral is much heavier than the other sulphates here considered and this constitutes a discriminating test in large specimens; it does not effervesce with acid, which distinguishes it from calcite.

Celestite generally appears in granular masses or as an aggregate of coarse crystals. Some degree of cleavage is usually apparent. Colour white or cream.

These sulphates seldom occur free of impurity in the rock-form; every gradation is met with between the slightly contaminated mineral substance to those developments in which sands, marls, clays, shales, limestones, etc., are intimately associated; various stages of replacement of limestone by the sulphates are possible and are observed.

In some cases it will be found that neither megascopic nor microscopic examination will result in positive identification of each mineral without recourse to physical and chemical tests. The variations of these deposits are very great and the possibility of more than one species being closely associated with another in the same sample,

renders it always desirable to conduct such confirmatory tests. At the same time much more can be done with thin sections under the microscope than is generally realized with these materials.

Text. Gypsum: saccharoidal; smooth; rough; friable; earthy; fibrous. Anhydrite: schistose; fibrous; scaly. Barite: fine; crystalline; granular, sometimes laminated. Celestite: granular; coarse, cavernous; smooth, crystalline.

Min. Comp. Gypsum: impurities commonly iron-ore, silica, calcite, clay. Anhydrite: impurities are gypsum, rock-salt, calcite, iron-ores, etc. Barite: impurities commonly silica, metallic ores, hematite, marl, sandstone, etc. Celestite: other sulphates, baryto-celestite, baryto-calcite, limestone, metallic ores, etc.

Micro. Gypsum often presents a 'porphyritic' structure in thin section under the microscope, when large, prismatic crystals are embedded in a fine crystalline gypsum ground-mass; the large crystals may or may not exhibit tendencies to parallel orientation, usually not. Other modes of occurrence recall the 'ophitic' structure of igneous rocks; in this case large platy gypsum crystals enclose well-formed euhedra. Mutually interferent crystalline types present a granulitic structure. Bunches of fine gypsum needles may form in irregular fashion or as spherulites or partial spherulites, the latter displaying a radial structure. If anhydrite is present, it usually stands out clearly by virtue of its higher refractive index (gypsum is lower than Canada balsam) and strongly developed cleavages. Specks of iron-ore, veins of other minerals, patches of distinctive colouring matter, are all common features of this rock-type.

Anhydrite is usually much more coarsely crystallized than gypsum, often in very marked rectangular, prismatic crystals packed together, often orientated in one direction within the boundaries of distinct aggregates. A pseudo-cubic cleavage is normally conspicuous. Other modes of occurrence are spherulitic, radial, irregular clusters, granular (when the rock is made up of scattered stumpy rectangular grains set in an extremely uniform matrix), aggregates of rounded (? corroded) grains and 'feathery' forms. In many examples every stage in the conversion of anhydrite to gypsum may be detected; alternating layers of anhydrite and gypsum are characteristic in some developments, yielding a laminar structure. The passage of limestone into anhydrite may be observed in appropriate examples, especially in dolomitic rocks.

Barite varies considerably from coarsely crystalline types (somewhat rare) to aggregates of mutually interferent crystals of prismatic or granular habit; sometimes the mineral is extremely compact and almost cryptocrystalline. A tendency to develop curved laminae is not uncommon. Impurities are on the whole commoner than with gypsum and anhydrite and are frequently identifiable as definite minerals or rock-particles. The earthy type is hard to distinguish from other sulphates by microscopical means alone; as, in fact, are often the crystalline developments; sometimes the alternating glassy and dull white, opaque lustre by reflected light—exhibited by certain forms of the mineral—is sufficiently diagnostic. It has a much higher refrac-

tive index than either gypsum or anhydrite. Although possessing similar cleavages to the latter, it seldom displays the markedly 'cubic' structures of that mineral.

Celestite is so very close in its properties to anhydrite that microscopical distinction is seldom possible; confirmatory tests should always be sought if this mineral is suspected. A bluish tinge to the platy crystals or to the fibrous forms (if developed) is very characteristic; the occurrence of scattered aggregates of fine, fibrous crystals in an otherwise homogeneous granular ground-mass, is suggestive of celestite, while in most examples the interference colours are of a lower order than anhydrite or barite.

Types. *Gypsum*: Permian, Kirkby Thore, Westmorland¹; from the Upper Marls (Permian) of Nottinghamshire and Yorkshire; from the Saliferous Marls (Permian) of Durham; from the Keuper Marls (Trias) of Nottinghamshire²; Derbyshire, Leicestershire etc.; from the Purbeck (Sub-Wealden Boring), near Battle, Sussex (free of anhydrite)³.

Anhydrite: localities as above, except Sussex⁴.

Barite: chiefly as vein-stone from Palaeozoic formations in Northumberland, Durham, Westmorland, Shropshire and Welsh Borders; residual material (Carboniferous Limestone) Bradwell Moor, Derbyshire; concretionary crystalline masses in Fuller's earth, Nutfield, Surrey⁵.

References

¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 3, 1915.

² W. A. Richardson, *Miner. Mag.*, 19, 1920, p. 77, and 1921, p. 196.

^{3, 4, 6} *Mem. Geol. Surv., op. cit.*

⁵ *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 2, 1916.

General Reference

A. W. Grabau, *Principles of Salt Deposition* (McGraw-Hill, New York), 1920.

(C4.3) NITRATES AND BORATES

[Pl. 57F, between pp. 288-289]

Nitrates are exemplified by the sodium nitrate or 'caliche' deposits of Chile and Peru, the borates by borax (or the crystallized mineral 'tincal') of volcanic origin in Tuscany, etc. From a petrological standpoint, these are comparatively unimportant rocks. The commonest example, soda nitre (Nitratine), is a white, grey or yellow, soft, rather earthy material; it is crystalline, like calcite, and 'twinkles' with plane polarized light. There are many varieties of nitrate compounded with calcium, magnesium salts, etc., for which reference must be made to appropriate literature (see below). Borax crystallizes in the monoclinic system and occurs as fine, slender crystals embedded in mud. 'Tincal' is the crude mineral.

General References

- R. A. F. Penrose, *Journ. Geol.*, **18**, 1910.
 A. W. Grabau, *Principles of Salt Deposition* (McGraw-Hill, New York), 1920.
 F. W. Clarke, *Data of Geochemistry, U.S. Geol. Surv., Bull. 770*, 1924, p. 243.
 G. W. Tyrrell, *Principles of Petrology* (Methuen, London), 1926, p. 232.

CHAPTER III

THE CLAY MINERALS

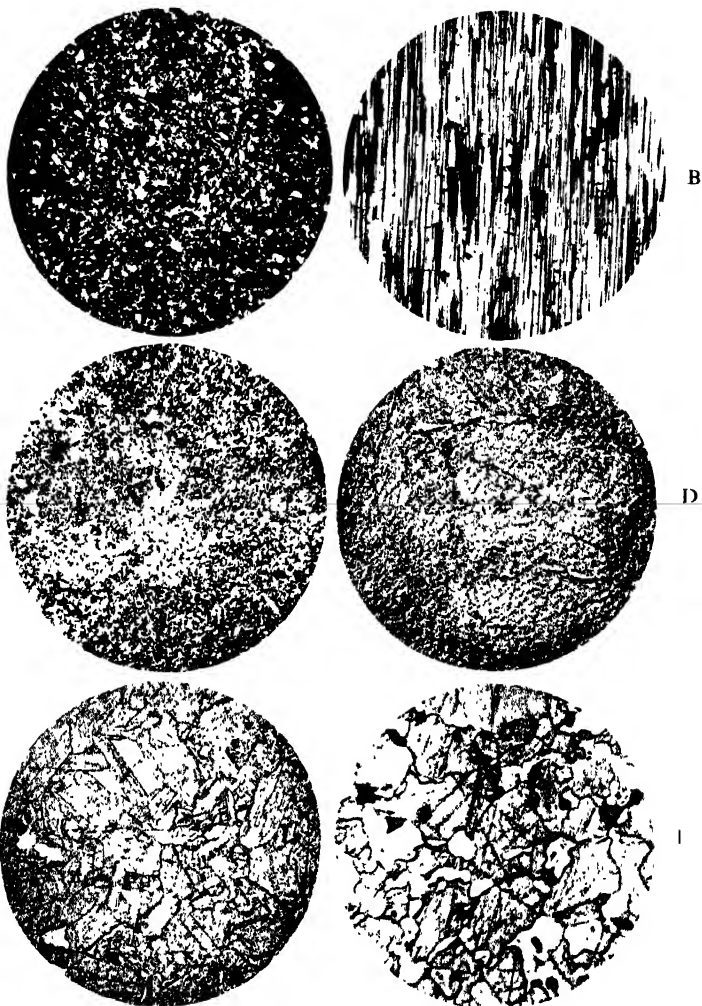
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Introduction—Structure and Classification—Properties of Clay Minerals and their Use in Identification—Ion-exchange Capacity—Water Relationships—Heat Effects in Clay Minerals—Thermal Curves and Differential Thermal Analysis—X-ray Diffraction—Infra-red Absorption—The Kaolin Group—Kaolinite—Dickite—Nacrite—Halloysite—Anauxite—Allophane—Chamosite—The Micaceous Clay Minerals—Hydrous Mica (Illite)—Glauconite (and Celadonite)—Montmorillonite Group—Vermiculite—Chlorite Group—Mixed-layer Minerals—Palygorskite (Attapulgitite) and Sepiolite—Minerals associated with the Clay Minerals—Occurrence of Clay Minerals—Clay Minerals in Soils—The Marine Environment—Clays of Hydrothermal Origin—Clay Minerals in Loess—Clay Minerals in Sedimentary Rocks—Various types of Residual and Transported Clays—Future Research in Clay Mineralogy—Bibliography.

INTRODUCTION

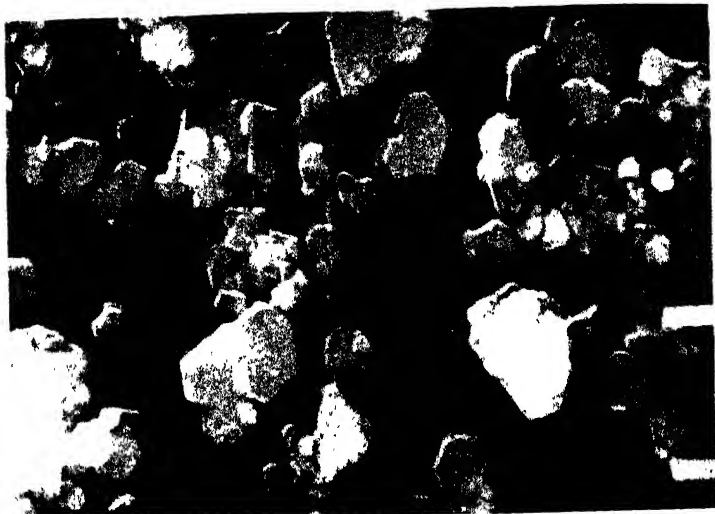
WITH the possible exception of quartz, clay minerals are the commonest of all minerals. Clay minerals are formed by alteration of primary rock minerals by weathering processes or by hydrothermal solutions. The kind of clay mineral formed depends on composition of the parent mineral and on the physicochemical environment in which the alteration takes place. Clay minerals can occur scattered through rocks of various kinds or in deposits which are commercially valuable. Deposits of clay may consist of only one species, *e.g.* bentonites formed by alteration of volcanic ash (western United States), or kaolins produced by hydrothermal alteration (Cornwall); but clays are often mixtures of various clay-mineral species and of other minerals such as quartz, feldspar, volcanic glass, cristobalite, iron oxides, gibbsite, organic matter, etc.

The clay minerals are extremely fine grained. This makes their identification and study difficult. Many clay minerals have similar chemical compositions, but differ in crystal structure. Examination by X-ray diffraction has provided the most satisfactory method of identification. The study of clay minerals by X-ray diffraction has increased enormously since wide-range goniometer diffractometers became available after World War II. The principal methods used in the identification of clay minerals are summarized in this chapter.



SULPHATE AND NITRATE

- A Gypsum (Permian), Kibbs Thore, Cumberland * [x 25]
 B "Satin Spar" (Fibrous Gypsum), Nottinghamshire * [x 25]
 C Gypsum (Purbeckian), Sub-Wealden Boring, Sussex.* [x 15]
 D Celestite, Yate, Gloucestershire [x 15]
 E. Barite, Patterdale, Cumberland [x 14]
 F Nitrate ("Nitratine"), Antofagasta, Chile [x 20]
 [*Crossed Nicols]



ELECTRON-MICROGRAPH OF KAOLINITE.

Macon, Georgia. Shadowed with Cr. at 18-19,000.
Photo by Jane Armstrong, State Geological Survey of Kansas.



ELECTRON-MICROGRAPH OF HALLOYSITE.

Ness County, Kansas. Shadowed with Cr at 18 - 22,000
Photo by Ada Swineford, State Geological Survey of Kansas



ELECTRON-MICROGRAPH OF LITHIAN

Lithian Illite. Shadowed with Cr. at 18 19,500
Photo by Jane Armstrong, State Geological Survey of Kansas

There is now an extensive literature on clay minerals and their identification, on their occurrence in soils, in weathered rocks, in sediments, and in sedimentary rocks, and on their properties (ion exchange capacity, colloidal behaviour, plasticity, dehydration, etc.). A selected bibliography at the end of this chapter contains the most important reference books and research results published to the end of 1955.

STRUCTURE AND CLASSIFICATION

Although the principal clay minerals were recognized and described long before X-rays were discovered, X-ray diffraction studies of crystal structure have provided the key to the various groups of minerals. The symposium edited by G. W. Brindley* in 1951 collected all X-ray data on clay minerals that were then available. As a result, a number of different groups of clay minerals were recognized. All are silicate minerals falling structurally into two main groups, known as the kaolin group and mica group respectively. These groups are made up of two different kinds of units, a silicon-oxygen tetrahedron and an aluminium-oxygen-hydroxyl octahedron. In the tetrahedron, the silicon ion is situated within four oxygen atoms and the bond between silicon and oxygen is strong. Within a tetrahedron, silicon-oxygen distance is about 1.6\AA and oxygen-oxygen distance is 2.6\AA . Sheets are formed by linking three corners of each tetrahedron to neighbours and this results in a hexagonal network. Such sheets form the basis of a large variety of flaky minerals, *e.g.* micas. The octahedral unit consists of a cation surrounded by six oxygens or hydroxyls; the cation is generally aluminium but may be magnesium or iron. Normal oxygen-oxygen is 2.6\AA and in this structural unit hydroxyl-hydroxyl distance is 2.94\AA ; the space available for the cation in octahedral co-ordination is about 0.61\AA .

When the internal cation is aluminium only, two-thirds of possible positions are filled to balance the structure, which then has the formula $\text{Al}_2(\text{OH})_6$, *i.e.* gibbsite. With magnesium, all positions are filled to balance the structure and the formula is $\text{Mg}_3(\text{OH})_6$, *i.e.* brucite. In describing clay mineral structures, the octahedral unit is often referred to as either the gibbsite or the brucite layer, depending on the cation present. The arrangement of the two kinds of units is shown in Fig. 50, from which it can be seen that silicon tetrahedra have definite apices, whereas aluminium octahedra are flat. An aluminium octahedral sheet, consisting of linked octahedral units, is combined with one or more sheets of linked silicon tetrahedral units to produce the fundamental structural

* *X-ray Identification and Crystal Structure of Clay Minerals* (Mineralogical Society, London), 1951.

patterns of the clay minerals. When there is one silicon sheet combined with one aluminium sheet, this is known as a 1-1 layer lattice; it is often spoken of as the kaolinite type, since minerals of the kaolin group have this structure. When there is one aluminium sheet combined with two silicon sheets, this is known as the 2-1 layer lattice and it is characteristic of mica and other minerals having this arrangement, *e.g.* hydrous mica (illite), montmorillonite, vermiculite, glauconite and celadonite. G. W. Brindley and D. M. C. MacEwan* consider that there are no

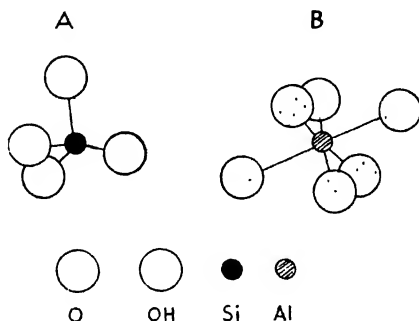


FIG. 50. The two structural units of the clay minerals.

A. Silicon-oxygen tetrahedron.

B. Aluminium-oxygen-hydroxyl octahedron.

(Note: The symbols for the various ions are those used in all succeeding figures in this chapter except where otherwise stated.)

sharp lines of demarcation between micas proper, hydrous micas (a broad term covering illite and such mixed layer minerals as bravaisite), and montmorillonite. It should be noted, however, that these minerals can be divided into two groups: the dioctahedral, in which two-thirds of the positions in the octahedral unit are filled by cations, and trioctahedral, in which all three positions are filled. Belonging to the dioctahedral group are muscovite, hydrous mica, montmorillonite, glauconite and celadonite; the trioctahedral group contains biotite and vermiculite.

There are two other combinations of layers in clay minerals: in one a brucite layer is present between mica layers; this gives rise to the structure of chlorite; in the other, the silicon tetrahedra are arranged in a chain structure similar to that of the amphiboles and linked together by octahedral groups of oxygens and hydroxyls containing Al and Mg atoms, such as occur in the palygorskite (attapulgite)-sepiolite groups.

* *Ceramics*, (Brit. Ceram. Soc., England), 1953, p. 15.

TABLE 1
CLASSIFICATION OF THE CLAY MINERALS¹

Structural Group	Layer Silicates				Chain Silicates
	Kaolin Group 1-1	Mica Group	Chlorite Group	Mixed Layer	Palygorskite
Minerals	Kaolinite Dickite Nacrite Halloysite 2H ₂ O Halloysite 4H ₂ O 'Fireclay mineral' ² Anauxite Allophane Chamosite ³	Hydrous mica (illite) Glaucanite Celadonite Montmorillonite Group Vermiculite	Chlorite (poly-varietal) Soil chlorites Swelling chlorite Chamosite ³	Rectorite Hydrobiotite Many different types of mixed-layers recorded	Attapulgite Sepiolite

¹ After G. W. Brindley (in part), Identification of Clay Minerals by X-ray Diffraction Analysis, *Proc. 1st Nat. Conf. Clays and Clay Tech., Calif. Dept. Nat. Res. Bull.*, **169**, 1955, p. 119.

² The 'Fireclay mineral' is a disordered kaolinite.

³ Chamosite belongs structurally to both the Kaolin and to the Chlorite Group (see description, p. 315).

The clay minerals in soils are often combinations of two types of layers, *e.g.* inter-layered vermiculite and chlorite, or kaolinite and montmorillonite. Refinement in techniques has indicated that such mixed-layer minerals are rather common. In addition to the structural types described above, there are amorphous clay minerals, *e.g.* allophane, which do not reflect X-rays.

Classification of clay minerals is not yet entirely satisfactory. R. E. Grim* based one classification on the structural types. G. W. Brindley† used both structure and chemical composition; a modification of his classification is given in Table 1; he does not include swelling varieties of the mica structural group (montmorillonite and vermiculite) in a separate category, in which they probably should be placed, because of the presence of water layers between the sheets. Until the structure of soil chlorites and vermiculites has been more fully investigated, no final classification can yet be made. Additional details of structure of individual clay minerals can be found in G. W. Brindley‡ and R. E. Grim§.

* *Clay Mineralogy* (McGraw-Hill, New York), 1953, p. 27.

† *Op. cit.*, 1955, p. 34.

‡ *Op. cit.*, 1951.

§ *Op. cit.*, 1953.

PROPERTIES OF CLAY MINERALS AND THEIR USE IN IDENTIFICATION

As with other minerals, certain properties are characteristic of clay minerals as a whole. The most important, structure, has been briefly outlined above. Structure largely determines many other properties, *e.g.* X-ray diffraction, ion-exchange capacity, dehydration, swelling, etc.; chemical composition is of little value without structural interpretation.

The principal characteristics of clay minerals form the basis of methods used in their identification. These may conveniently be summarized as in Table 2.

TABLE 2
METHODS FOR THE IDENTIFICATION OF THE CLAY MINERALS

Property	Method	Description
Structure of crystal lattice	X-ray diffraction analysis	Basal cleavage and layer structure give reflections with X-rays, (00l) spacings, particularly in oriented aggregates. These reflections are 001, 002, etc., and can be easily recognized in powder photographs or diffractometer charts. The layer thickness determines type and therefore identifies the structural group to which a clay mineral belongs. Spacings of about 7, 10 and 14 Å are broadly characteristic of kaolin, mica and montmorillonite type minerals. Supplementary heating, chemical and glycol solvation tests are necessary for complete identification. For further particulars see G. W. Brindley ¹ , R. E. Grim ² , P. F. Kerr ³ .
Chemical Composition	Chemical analysis; ion-exchange capacity; exchangeable ions; decomposition by acids and alkalis.	Complete chemical analysis forms the basis of a formula for a mineral which, if calculated according to the method of C. S. Ross and S. B. Hendricks ⁴ for montmorillonites, gives the position of the negative charges and the amount required to balance the structure. Ion-exchange capacity is partly related to the species of clay mineral. Ions in exchange positions on or in the crystal lattice can be removed by replacing with another ion and the amount can be measured; the removed ions can be determined chemically (W. P. Kelley) ⁵ . Titration with acid and alkalis indicates the stability of clay minerals at certain concentrations and pH values (P. G. Nutting) ⁶ .

TABLE 2 (CONTD.)

Water content	Differential thermal analysis (D.T.A.)	Loss of water from clay minerals at various temperatures is measured. This water may be adsorbed, interlayer, or lattice OH water. In D.T.A., loss of water is shown by endothermic reactions measured as temperature change against that of an inert substance as temperature is raised at a fixed rate. There are characteristic temperatures for endothermic reactions of most clay minerals. An exothermic reaction occurs when reconstitution of the mineral occurs at high temperatures (P. F. Kerr ⁷ ; R. E. Grim ⁸ ; S. Speil <i>et al.</i> ⁹). Dehydration curves can be obtained in various ways to depict temperature at which loss of water takes place; such curves are characteristic of certain clay minerals (P. G. Nutting) ¹⁰ .
Optical properties	Petrological microscope	Refractive index and birefringence are sufficiently varied to be used for identification of larger particles of many clay minerals; some exhibit pleochroism, <i>e.g.</i> nontronite, glauconite (R. E. Grim) ¹¹ . Oriented aggregate techniques ¹² and orientation in an electrical field (C. E. Marshall) ¹³ can be used, but optical data alone are seldom sufficient to identify a clay mineral with certainty.
Shape of particles	Electron microscope	Kaolinite, dickite, nacrite, halloysite, hydrous micas, some members of the montmorillonite group, palygorskite (attapulgite) and other clay minerals, have characteristic shapes when photographed with the electron microscope. The enlargement is in the order of 15,000 to 75,000 times original size. (R. E. Grim ¹⁴ P. F. Kerr ¹⁵ ; T. F. Bates ¹⁶ .) Large grains of minerals in the kaolin group can often be identified with the petrological microscope (C. S. Ross and P. F. Kerr ¹⁷).

¹ *Op. cit.*, 1951. Also Identification of Clay Minerals by X-ray Diffraction Analysis, *Proc. 1st Nat. Conf. Clays and Clay Tech.*, Calif. Dept. Nat. Res., Bull. 169, 1955, p. 119.

² *Op. cit.*, 1953.

³ Clay Mineral Standards, *Amer. Pet. Inst. Proj.*, 49, Various Reports, 1949-1950.

⁴ *U.S. Geol. Surv. Prof. Paper* 205B, 1945.

⁵ Cation Exchange in Soils (Reinhold, New York), 1948.

⁶ *U.S. Geol. Surv., Prof. Paper* 197F, 1943.

⁷ *Op. cit.*, 1950.

⁸ *Op. cit.*, 1953.

⁹ *U.S. Bur. Mines Tech. Paper*, 664, 1945.

¹⁰ *U.S. Geol. Surv., Prof. Paper*, 197-E, 1943.

¹¹ *Op. cit.*, 1953, p. 279.

¹² R. E. Grim, *op. cit.*, 1953, p. 288.

¹³ *The Colloid Chemistry of the Silicate Minerals* (Academic Press, New York), 1949.

¹⁴ *Op. cit.*, 1953.

¹⁵ *Op. cit.*, 1950.

¹⁶ *Proc. 1st Nat. Conf. Clays and Clay Tech.*, Calif. Dept. Nat. Res. Bull., 169, 1955, p. 130.

¹⁷ *U.S. Geol. Surv., Prof. Paper* 165-E, 1931.

TABLE 2 (CONTD.)

Adsorption of colours	Staining with various dyes	Colours can be developed in certain clay minerals with aniline dyes, <i>e.g.</i> malachite green, safranin-Y, benzidine, para-amino phenol. Effects are due to acid-base reactions and to oxidation-reduction mechanisms (G. T. Faust ¹⁸ ; R. C. Mielenz <i>et al.</i> ¹⁹ ; C. G. Dodd ²⁰). Adsorption of methylene blue has been used as a measure of ion-exchange capacity (R. H. S. Robertson and R. M. Ward ²¹).
Adsorption of organic molecules	Saturation with organic ions	Ionic reactions affect cation-exchange capacity, expand the lattice of montmorillonite (this is used as a means of identification by X-rays), reduce water-adsorption capacity, thereby altering shape of the D.T.A. curves (R.E.Grim ²²). Data from D. M. C. MacEwan ²³ indicate some of the effects. In soil clays, inter-layering of organic matter and some clay-minerals occurs; this alters ion-exchange capacity.
Infra-red absorption	Infra-red spectrophotometer	Characteristic absorption bands are given by the various clay minerals. Techniques have not been standardized and experimentation is still necessary. A review of results is given by P. G. Nahin ²⁴ and curves obtained for some of the Reference Clay Minerals are in A.P.I. Project 49 ²⁵ .

¹⁸ U.S. Bur. Mines, *Rep. of Invest.*, 3522, 1940.

¹⁹ *Amer. Pet. Inst., Proj. 49, Prel. Rep. 7*, 1950.

²⁰ *Proc. 1st Nat. Conf. Clays and Clay Tech., Calif. Dept. Nat. Res., Bull.*, 169, 1955, p. 105.

²¹ *Journ. Pharm. and Pharmacol.*, 3, 1951, p. 27.

²² *Op. cit.*, 1953, Ch. 10.

²³ *Trans. Farad. Soc.*, 44, 1948, p. 349. Also in G. W. Brindley, *op. cit.*, 1951, p. 86.

²⁴ *Proc. 1st Nat. Conf. Clays and Clay Tech., Calif. Dept. Nat. Res., Bull.*, 169, 1955, p. 112.

²⁵ *Prel. Rep.*, 8, 1950.

Various other methods of identification of clay minerals have been employed, as summarized by R. E. Grim*. Other diagnostic properties of clay minerals will be found under appropriate mineral names in Chapter I.

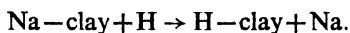
Ion-exchange capacity, water relationships, thermal reactions, differential thermal analysis and X-ray diffraction of clay minerals will now be described in more detail than is possible in Table 1.

* *Op. cit.*, 1953, pp. 295-312.

ION-EXCHANGE CAPACITY

The fact that ammonia was adsorbed by soils led to the discovery of ion-exchange phenomena in the clay minerals. It was in 1850 that H. S. Thompson's and J. F. Way's observations and experiments were published; these explained in part how the exchange of one ion for another took place (W. P. Kelley)¹. It was believed that soils contained amorphous material which acted as the exchanger; a little later it was discovered that a similar ion-exchange took place in zeolites, so that quite naturally the idea of soil zeolites occurred, and it persisted until 1930 when the crystalline nature of the clay material was found by X-ray diffraction (S. B. Hendricks and W. H. Fry)².

Quite simply stated, ion-exchange can be shown in the following equation:



The ion-exchange capacity is defined as the amount of ion exchanged, expressed in milliequivalents per gram, or per 100 grams of clay at pH 7.

The actual exchange of cations is dependent on the structure and chemical composition of the clay mineral concerned in the reaction and on the environment in which the exchange takes place, *i.e.* on the ions in the solution in which the mineral is placed, on the ions already present in the clay mineral structure, and on several other factors. Other things being equal, bivalent ions are more readily adsorbed than univalent ions. Ions vary in their relative ease of replacement:



but there is no constant series for any one of the clay minerals. In most soils calcium is the dominant replaceable ion, but others such as magnesium, sodium and potassium are nearly always present in varying amounts. There is little information concerning the replaceability of the trivalent ions such as Fe^{+3} and Al^{+3} .

Anion exchange can also take place, and certain anions such as PO_4^{3-} can be adsorbed on clay minerals, but it is not proposed to discuss anion adsorption here, and the reader is referred to the references at the end of this section, p. 359.

The cation exchange capacity of the various clay minerals has been found to be as follows (after R. E. Grim with certain additions)³:

References

¹ *Op. cit.*, 1948.

² *Soil Sci.*, **29**, 1930, p. 457.

³ *Op. cit.*, 1953, p. 129.

MINERAL	STRUCTURAL CONTROL	MILLIEQUIVALENTS PER 100 g. AT pH 7
Kaolinite	Unsatisfied bonds on edges of lattice	3—15
Halloysite 2H ₂ O	Unsatisfied bonds on edges of lattice	5—10
Halloysite 4H ₂ O	Unsatisfied bonds on edges of lattice plus effect of water layer	40—50
Montmorillonite group	Substitutions in the lattice and broken bonds on edges	70—100+*
Hydrous micas (illite)	Substitutions in the lattice and broken bonds on edges, plus deficiency of K ⁺ ion between sheets	10—40
Vermiculite	Replacement of interlayer cations, substitution and broken bonds	100—150
Chlorite	No data, possibly like hydrous mica	10—40
Glauconite	As in hydrous mica	11—20
Palygorskite group	Replacement of Si by Al; exchange site similar to that in zeolites, <i>i.e.</i> in channels in the structure	20—30
Allophane	Unsatisfied bonds	69—73

The underlying reasons for ion-exchange in the kaolinite and in the montmorillonite groups can now be discussed. Ion-exchange takes place if the layers of which the clay minerals are composed are not electrically neutral, *i.e.* if there is an excess or deficiency of charge on the structure as a whole. In kaolinite, for example, the charges on the layers are arranged as follows:

	Charges	
Si-tetrahedron	$\left\{ \begin{array}{l} 6 \text{ O}^{-2} \\ 4 \text{ Si}^{+4} \end{array} \right.$	$\left. \begin{array}{l} -12 \\ +16 \end{array} \right\} \begin{array}{l} -28 \\ +28 \end{array}$
Al-octahedron	$\left\{ \begin{array}{l} 4 \text{ O}^{-2} + 2(\text{OH})^{-1} \\ 4 \text{ Al}^{+3} \\ 6 (\text{OH})^{-1} \end{array} \right.$	$\left. \begin{array}{l} -10 \\ +12 \\ -6 \end{array} \right\} \begin{array}{l} -28 \\ +28 \end{array}$

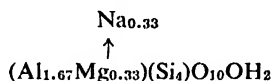
The structure is neutral and ion-exchange is therefore small and is due to broken bonds on the edges of the sheets; from this it follows that the smaller the particle size, the more broken bonds and the higher the ion-exchange capacity.

In montmorillonite, which has a high ion-exchange capacity, negative charges arise because of substitution of Al for Si in the tetrahedral layer, and of Mg⁺², Fe⁺³, Fe⁺² for Al⁺³ in the octahedral layer. The exchangeable ions are situated between the silicate layers

* Certain members of this group such as saponite, sauconite, and stevensite have a much lower exchange capacity than other montmorillonites, because of the filling of octahedral and tetrahedral positions.

where they are associated with the interlayer water. The layers are not held together by K^+ ions as in the micas. C. S. Ross and S. B. Hendricks¹ have shown the importance of isomorphous substitution in the montmorillonite group and its relation to exchange capacity.

Montmorillonite consists structurally of silicate layers formed of double sheets of linked silicon-oxygen tetrahedral groups joined by aluminium-oxygen-hydroxyl octahedral groups which form a rigid framework. For every 12 (oxygen+hydroxyl) ions, i.e. $10 O^{-2} + 2(OH)^{-}$, there are four tetrahedral positions. These positions must be completely filled, predominantly by Si ions, which can, in part, be replaced by Al ions. Correspondingly there are three positions having octahedral co-ordination, of which 2-3 may be occupied by Al^{+3} , Fe^{+3} , Fe^{+2} , Mg^{+2} , Ni^{+2} and Li^{+2} . If, in a neutral framework, an ion of lower valence takes the place of one of higher valence, $Si^{+4} \rightarrow Al^{+3}$, $Al^{+3} \rightarrow Mg^{+2}$, or $Mg^{+2} \rightarrow Li^+$, a negative charge will be developed. This charge can be neutralized either by further addition of positive ions external to the silicate layer, or by substitution of O^{-2} by $(OH)^{-1}$. The last, if present, would be expected only for those O ions that are present in tetrahedral co-ordination about Al and are not shared with other tetrahedral groups. One of the many examples of such exchanges given by C. S. Ross and S. B. Hendricks² is:



The lack of balance in the charge on the lattice arises from the substitution of Al^{+3} by Mg^{+2} .

Following C. S. Ross and S. B. Hendricks³, G. W. Brindley and D. M. C. MacEwan⁴ have summarized the structural reasons for cation exchange in the clay minerals as follows:

- (1) Unsatisfied valencies produced by broken bonds at surfaces and edges of particles.
- (2) Unbalanced charges caused by isomorphous substitution of atoms.
- (3) Dissociation of structural $-OH$ radicals, the H of which may be replaced by other cations.
- (4) Accessibility of structural cations (other than H^+) which become exchangeable under appropriate conditions.

References

¹ U.S. Geol. Surv., *Prof. Paper* 205B, 1945.

² *Op. cit.*, 1945.

³ *Op. cit.*, 1945.

⁴ Structural Aspects of the Mineralogy of Clays and Related Silicates, *Ceramics* (British Ceramic Society), 1953, p. 15.

General References

There is a very extensive literature on ion-exchange, particularly in soils. In the following general references extensive bibliographies will be found.

- D. Carroll, Ion Exchange in Clays and other Minerals, *Geol. Soc. Amer. Bull.* **70**, 1959, p. 479.
J. E. Giesekeing, The Clay Minerals in Soils, *Advances in Agronomy*, **1**, 1949, p. 159.
S. B. Hendricks, Base Exchange of Crystalline Silicates, *Ind. Eng. Chem.*, **37**, 1945, p. 625.
W. P. Kelley, *Cation Exchange in Soils* (Reinhold, New York), 1948.
D. R. Lewis, Ion Exchange Reactions of Clays. Clays and Clay Technology, *Calif. Dept. Nat. Res., Bull.* **169** (*Proc. 1st Nat. Clay Minerals Conf.*).
C. E. Marshall, *The Colloid Chemistry of the Silicate Minerals* (Academic Press, New York), 1949. The Electrochemistry of Clay Minerals in Relation to Pedology, *Trans. 4th Intern. Cong. Soil Sci.*, **1**, 1950, p. 71.
L. Wiklander, Cation and Anion Exchange Phenomena, *Chemistry of the Soil* (Rienhold, New York), 1955.

WATER RELATIONSHIPS

There are three kinds of water associated with the clay minerals: water adsorbed on the surfaces of the particles, interlayer and inner-channel water and hydroxyl water. The surface-adsorbed water and the interlayer-water are loosely held, and can be driven off at low temperatures (100–150° C.), but the hydroxyl water requires a much higher temperature for its removal.

Many properties of clays, such as plasticity, swelling and colloidal properties generally, depend on the low temperature water. The adsorbed water is held as an oriented layer on the surfaces of the individual clay flakes or as interlayer water. S. B. Hendricks and M. E. Jefferson¹ described the water layers on the surfaces as water molecules joined into hexagonal groups oriented by the nature of the bond between the hydrogen and oxygen atoms in the water to the oxygen and hydroxyl groups of the clay mineral. The oriented water layer extends outwards for some distance from the surface of the clay micelle. Other theories have also been postulated (see R. E. Grim²), but there is no agreement at present as to the configuration of the adsorbed water.

The physical state of the adsorbed water is not like that of liquid water; there is an optimum amount of water which produces the best bonding for clay particles one with another. This is a matter of common observation, as for example, in the optimum moisture content of ploughed clayey soil, and in moulding. The adsorbed water is believed to be in a solid state (H. W. Winterkorn³).

¹ Structure of Kaolin and Talc-Pyrophyllite Hydrates and their Bearing on the Water Sorption of Clays, *Amer. Mineral.*, **23**, 1939, p. 863.

² *Op. cit.*, 1953, pp. 167–171.

³ The Condition of Water in Porous Systems, *Soil Sci.*, **55**, 1943, p. 109.

The thickness of the adsorbed water, both surface and inter-layer, depends on the exchangeable cation; thus R. E. Grim and F. L. Cuthbert¹ found that for Na-montmorillonite the thickness is about 7.5Å, and for Ca-montmorillonite it is 10Å. It is believed that the water-layer on kaolinite is not thicker than that on montmorillonite.

Inter-layer water adsorption and expansion in montmorillonite has been described by I. Barshad² as taking place in five stages. In samples saturated with cations of equal charge but varying in size, the larger the ionic radius the higher the relative humidity at which expansion occurs. Expansion beyond a unimolecular water layer does not take place in montmorillonite saturated with K⁺, Rb⁺ or Cs⁺ ions. The very large surface areas of clay minerals are important in water adsorption. For additional details I. Barshad's paper should be consulted³.

The hydroxyl water, which is a part of the lattice structure, can be removed by heating to about 300°C., and is measured by dehydration curves or differential thermal analysis. The temperature at which it is removed is characteristic for each group of clay minerals, and is used as a means of identification.

HEAT EFFECTS IN CLAY MINERALS—THERMAL CURVES AND DIFFERENTIAL THERMAL ANALYSIS

Because of the chemical and physical composition of the clay minerals, certain changes take place when their temperature is raised. One such effect at low temperatures is the loss of interlayer water in such minerals as halloysite (4H₂O) and montmorillonite. At higher temperatures the mineral structure will be destroyed and a new mineral or minerals will be formed. It has been found that the temperatures at which such changes take place are characteristic for certain of these minerals. The changes, such as loss of water, can be shown as thermal curves in which loss of water is plotted against temperature (these curves are also known as dehydration curves). This procedure can be carried out very simply by heating to a constant weight at any particular temperature, or by using apparatus such as the Chevenard balance. Dehydration or thermal curves for several minerals are shown in Fig. 51.

Another means of showing such changes is by differential thermal analysis, which is based on measurement of the effects of heat applied to a mineral or mixture of minerals, compared with the

¹ *Journ. Amer. Ceram. Soc.*, **28**, 1945, pp. 90-95.

² Adsorptive and Swelling Properties of Clay-Water System, *Proc. 1st Nat. Conf. Clays and Clay Tech., Calif. Dept. Nat. Res., Bull.* **169**, 1955, p. 70.

³ *Op. cit.*, 1955, p. 70.

effect on an inert substance such as alundum or calcined clay. This measurement is made by means of a thermocouple and the results are recorded automatically. The rise in temperature is kept at a constant rate, usually at about 10°C. per minute (details of the apparatus used can be obtained from the references cited on p. 302).

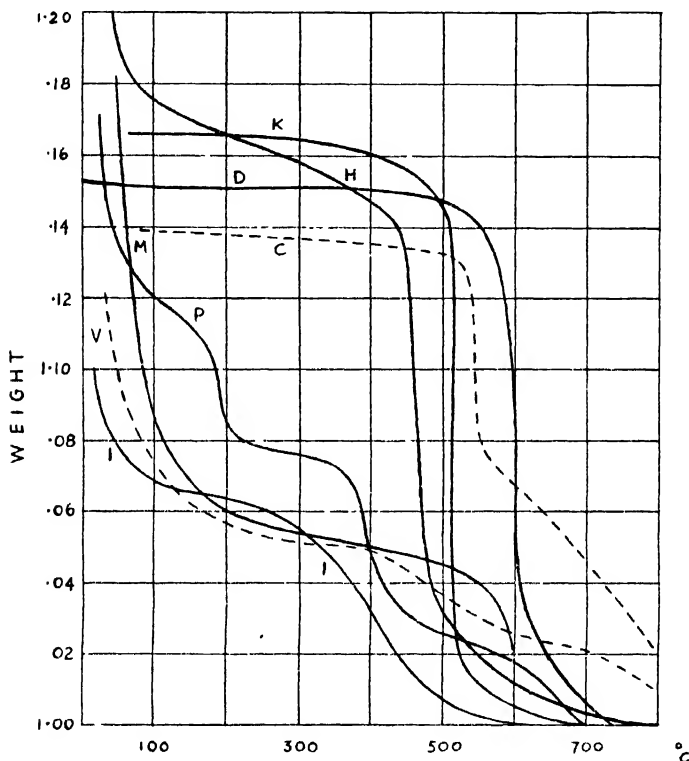


FIG. 51. Dehydration or thermal curves of various clay minerals.

C Chlorite; D Dickite; K Kaolinite;
H Halloysite; M Montmorillonite;
P Palygorskite; V Vermiculite; I Illite.

(After P. G. Nutting, 1943.)

Differential thermal analysis is a very satisfactory method of identification of the clay minerals, since most of them have characteristic endothermic and exothermic reactions at definite temperatures or within a definite temperature range. Such information is given in the descriptions of the clay minerals in a later part

of this chapter. Typical differential thermal analysis curves for some of the clay minerals are given in Fig. 52.

In addition to identifying any particular clay mineral, measurement of the area of the principal endothermic peak gives a quantitative measure of the amount of that mineral present in the sample being examined. The area is measured with a planimeter; the total heat effect equals the product of the specific heat of reaction and the mass of reacting material, and it is therefore proportional to the percentage of reacting material in a given weight of sample.

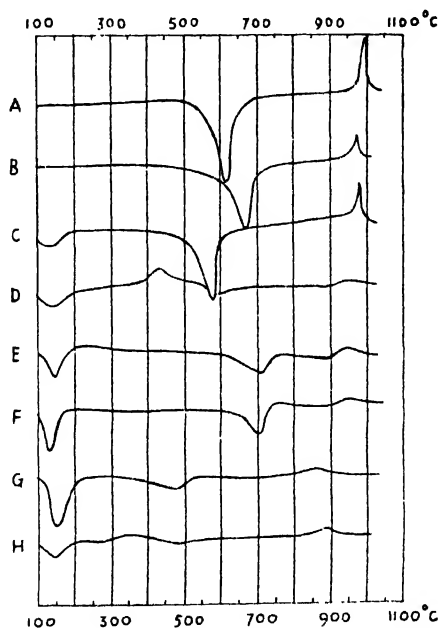


FIG. 52. Differential thermal analysis curves for standard clay minerals. Peaks below the zero line are endothermic reactions; those above are exothermic reactions.

- A Kaolinite, Lewistown, Montana (No. 17).
- B Dickite, Ouray, Colorado (No. 14).
- C Halloysite (blue), Bedford, Indiana (No. 12a).
- D Illite, Fithian, Illinois (No. 35).
- E Montmorillonite, Upton, Wyoming (No. 25a).
- F Montmorillonite, Belle Fourche, South Dakota (No. 27).
- G Nontronite, Manito, Washington (No. 336).
- H Attapulgite, Attapulgis, Georgia (No. 43).

(From P. F. Kerr, J. L. Kulp and P. K. Hamilton (1949). Courtesy of the American Petroleum Institute.)

(Note: The sample numbers are those of the A.P.I. Clay Mineral Standards.)

It is not proposed to discuss differential thermal analysis in more detail here, as there is an extensive literature on the subject. In the United States, clay minerals described by the American Petroleum Institute, Project 49 (1949), are used as standards. Recently the Comité International pour l'Étude des Argiles (C.I.P.E.A.) has made a preliminary report on 'Standardization of Differential Thermal Analysis Technique'¹. Moreover the Mineralogical Society (Gt. Britain) had a symposium on Differential Thermal Analysis².

There is one other aspect of differential thermal analysis which is of interest; a small portable unit which can be used in the field was designed by S. B. Hendricks and others³ during World War II, specifically for exploring possible bauxite deposits. Very satisfactory results can be obtained with this instrument, provided it has been calibrated with standard clay minerals⁴.

General References

- L. H. Berkelhamer, An Apparatus for Differential Thermal Analysis, *U.S. Bureau of Mines, Rep. of Invest.*, **3762**, 1944.
- S. Speil, L. H. Berkelhamer, J. A. Pask and B. Davies, Differential Thermal Analysis, its Application to Clays and Other Aluminous Materials, *U.S. Bureau of Mines, Tech. Paper* **664**, 1945.
- G. T. Faust, Thermal Analysis of Quartz, and its Use in Calibration in Thermal Analysis Studies, *Amer. Mineral.*, **33**, 1948, p. 337.
- R. E. Grim, *Clay Mineralogy* (McGraw-Hill, New York), 1953, Ch. 9.
- P. F. Kerr, J. L. Kulp and P. K. Hamilton, Differential Thermal Analyses of Reference Clay Mineral Specimens, *Amer. Petrol. Instit. Proj.* **49**, *Clay Mineral Standards*, 1949.
- P. G. Nutting, Some Standard Thermal Dehydration Curves of Minerals, *U.S. Geol. Surv., Prof. Paper* **197E**, 1943, pp. 197-216.
- L. A. Dean, Differential Thermal Analyses of Hawaiian Soils, *Soil Sci.*, **63**, 1947, p. 95.

X-RAY DIFFRACTION

The principles of X-ray diffraction and their use in mineral identification are given in Vol. I, Ch. XIII, but additional information on the application of X-ray techniques to clay mineral identification is necessary because of the preparation required and the tests to be applied. The main groups of clay minerals can be identified in X-ray powder photographs or in diffractometer patterns fairly

¹ R. C. Mackenzie and K. R. Farquharson, Standardization of Differential Thermal Analysis Technique, *Compt. Rend., 19th Session Inter. Geol. Congress (Algiers)*, 1952, pp. 183-200.

² R. C. Mackenzie, *The Differential Thermal Investigation of Clays* (Miner. Soc., London), 1957.

³ S. B. Hendricks, S. S. Goldich and R. A. Nelson, *Econ. Geol.*, **41**, 1946, p. 64.

⁴ C. J. Parker, J. C. Hathaway and P. D. Blackmon, *U.S. Geol. Surv., Bull.* **1021-G**, 1955.

readily by consulting the data obtainable in 'X-ray Identification and Crystal Structures of Clay Minerals'¹, 'Clay Mineralogy'² and the Card Index compiled by the American Society for Testing Materials. One of the difficulties in identification is that in many natural occurrences, more than one clay mineral may be present. In soil colloids, for example, it is the rule rather than the exception for mixtures of clay minerals to be present, as pointed out by M. L. Jackson and others³.

Various methods are used in the preparation of clay minerals for X-ray examination; most of these aim at the separation of certain sizes of material by settling velocity (modifications of Stoke's law), or by using a standard type centrifuge or a Sharples super-centrifuge. Some investigators use a fraction less than 2μ in diameter, whereas others make separations at 1μ or at 0.5μ . A method used by the U.S. Geological Survey has been described by J. C. Hathaway⁴. The flow sheet of the procedures is given in Table 3.

This method has the advantage that it can be modified by taking the clay suspension from a soil mechanical analysis, or by utilizing the clay obtained from limestones by dissolving the carbonates with acetic or formic acid (HCl will attack many clay minerals).

The wide-range goniometer diffractometers now available have greatly facilitated the X-ray examination of clay minerals, both with regard to ease of manipulation and to time consumed. By placing diffractometer patterns obtained from oriented and un-oriented mounts and from different treatments one above the other on the same chart and using different coloured tracing inks, as suggested by C. D. Jeffries⁵, a complete picture can be obtained of the diffraction patterns of a mixture of clay minerals.

Routine procedure for X-ray examination of clay minerals has been outlined by J. C. Hathaway⁶. At least six X-ray diffractometer patterns are made for each sample as follows:

- | | | |
|--------------------------------|---|---|
| Clay fraction
($< 2\mu$) | { | <ol style="list-style-type: none"> 1. Untreated oriented aggregate 2. Oriented aggregate treated with ethylene glycol 3. Oriented aggregate heated to 400°C. 4. Oriented aggregate heated to 500°C. |
| Silt fraction
($2-62\mu$) | { | <ol style="list-style-type: none"> 5. Randomly oriented powder 6. Randomly oriented powder |

The oriented aggregates can be made by placing a small quantity of clay suspension on glass microscope slides and allowing the

¹ G. W. Brindley, *op. cit.*, 1951.

² R. E. Grim, *op. cit.*, 1953.

³ *Journ. Phys. Coll. Chem.*, **52**, 1948, p. 1237.

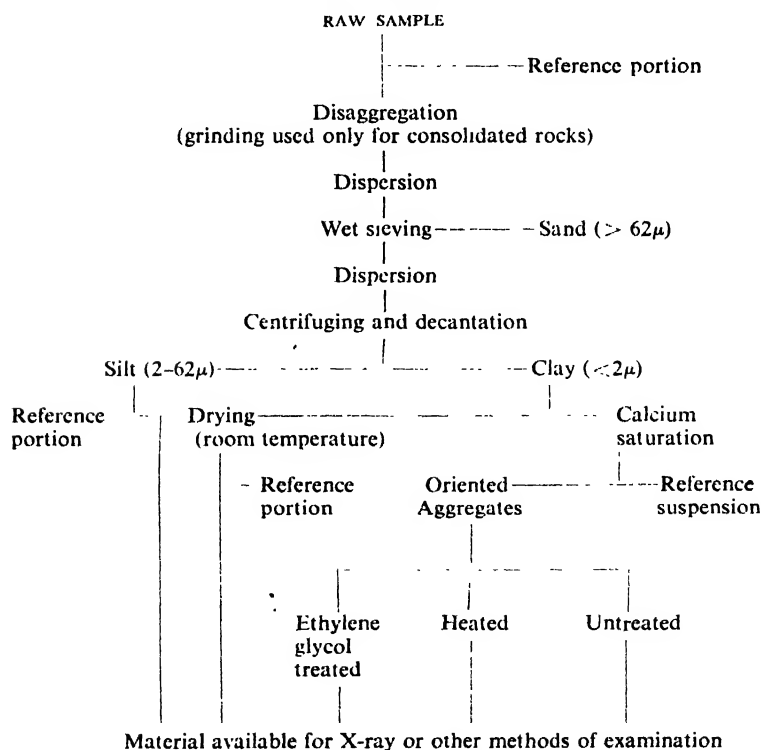
⁴ *Clay. Min., Bull.* **3**, 1956, p. 8.

⁵ *Soil Sci. Soc. Amer., Proc.* **14**, 1949, p. 378.

⁶ *Op. cit.*, 1956.

water to evaporate, but a more rapid method is that described by E. B. Kinter and S. Diamond¹ in which the clay suspension is placed on a fine porous porcelain tile in a special holder which fits inside the brass holders for 250 ml. centrifuge tubes. The water is removed by centrifuging and when dry, the tile can be placed in the diffractometer. If glass slides are used, and heating in a muffle furnace is part of the preparation, then Pyrex glass slides which are not affected by heat are advantageous. Small furnaces have now been designed to fit over the slide being exposed to the X-ray beams in a diffractometer, so that the clay being examined can be heated during the examination, the heating rate being calibrated with the chart speed. The effect of the heating is shown on the

TABLE 3
STEPS IN THE PREPARATION AND EXAMINATION OF
MATERIALS FOR IDENTIFICATION OF CONTAINED
CLAY MINERALS



¹ *Soil Sci.*, **81**, 1956, p. 111.

chart. One such furnace has been described by E. J. Weiss and R. A. Rowland¹.

The quantitative aspect of clay mineral identification is not yet satisfactory. Comparison of the line intensities in a powder photograph either estimated visually or measured with a photometer, will give some indication of the relative amounts of different clay minerals in a mixture. Standard mixtures are used for comparison; when these are prepared each mineral should have the same degree of crystallinity for the comparison to be valid, because the scattering effects of each mineral will then be approximately equal. The effect of orientation should be minimized. In diffractometer patterns, in which the line of a lattice plane reflection is replaced by a peak indicating the amount of a particular reflection plane, it would appear possible to use the area under the peak as a measure of the amount of the mineral present. G. Talvenheimo and J. L. White² and H. P. Klug and L. E. Alexander³ have discussed this method, and the former authors give evidence that a 5–10% accuracy is obtainable. The amount of X-ray reflection depends on the crystal structure and it was found that in mixtures of equal quantities (by weight), the ratios of the basal peak areas (using the lowest 001 peak for each mineral) for montmorillonite, kaolinite and hydrous mica are 5:1:1. Actual peak areas obtained by G. Talvenheimo and J. L. White⁴ are as follows:

<i>Montmorillonite</i>		<i>Kaolinite</i>		<i>Hydrous mica</i>	
%	Area	%	Area	%	Area
wt.	sq. in.	wt.	sq. in.	wt.	sq. in.
35.0	2.98	36.8	0.85	28.2	0.63

Using this 5:1:1 ratio, J. C. Hathaway and D. Carroll⁵ prepared a nomograph for obtaining the composition of a sample in per cent. by weight, from the basal peak areas measured on diffractometer patterns, using a Norelco diffractometer.

A comprehensive account of qualitative and quantitative estimations of clay minerals by X-ray diffraction methods has been given by W. D. Johns, R. E. Grim and W. F. Bradley⁶. Using a wide-range goniometer X-ray diffractometer, oriented samples containing a mixture of montmorillonite, chlorite, illite and kaolinite were

¹ *Amer. Min.*, **41**, 1956, p. 117.

² *Anal. Chem.*, **24**, 1952, p. 1784.

³ *X-ray Diffraction Procedures for Polycrystalline and Amorphous Materials* (Wiley, New York), 1954.

⁴ *Op. cit.*, 1952, p. 1788.

⁵ *Proc. 2nd Nat. Clay Conf. (Pub. 327, Nat. Acad. Sci. Nat. Res. Council, Washington, D.C.)*, 1954, p. 264.

⁶ *Journ. Sed. Pet.*, **24**, 1954, p. 242.

measured in the natural condition, solvated with ethylene glycol and heated to 450°C. The intensity values for basal reflections are direct counts which can be obtained with these types of diffractometers. The relative abundances, as judged by the relative intensities, were compared with the illite phase within each sample. Because these clay minerals have poor crystallinity, the intensity is taken as the observed intensities over a sequence of angles surrounding each maximum, since these give a more accurate reading than that of a single maximum. Another factor has also to be considered; W. F. Bradley¹ has shown that scattering from three-layer clay minerals at an angle corresponding to 17Å (expanded montmorillonite) exceeds by a factor of approximately four the reflected intensity of similar material contributing scattering at 10Å. Thus the intensity values for illite must be multiplied by a factor of four before direct comparison can be made with intensity values at 17Å. This is in agreement with the findings of G. Talvenheimo and J. L. White². It is believed that scattering distribution is sufficiently constant that the 3.5Å maximum for chlorite and kaolinite can be compared directly with the 3.3Å reflection for illite.

The method of calculating the quantities of clay minerals present in a mixed clay sample is as follows:

TABLE 4
METHOD OF CALCULATING THE QUANTITATIVE
COMPOSITION OF A MIXED CLAY SAMPLE³

Spacings	17Å	10Å	7Å	3.5Å	3.3Å	Comments
A. Relative Intensity Data*						
	480	20 80			55	Illite corrected Illite corrected for quartz
			45	45		
			30	30		Corrected for montmorillonite
			10	10		Kaolinite corrected for chlorite
			20	20		Chlorite

* Intensity values based on direct counts.

¹ *Anal. Chem.*, **25**, 1953, p. 727.

² *Op. cit.*, 1952.

³ W. D. Johns, R. E. Grim and W. F. Bradley, *op. cit.* 1954.

TABLE 4 (CONTD.)

B. Clay Mineral Composition				
Montmorillonite	Chlorite	Illite	Kaolinite	Comments
6.0	0.4	1.0	0.2	Parts per one part of illite
79	5	13	3	Approximate percentage of each constituent
7	0.5	1.0+	0.5-	Parts in ten of each constituent allowing 10% for material not registering

General References

G. W. Brindley, Identification of Clay Minerals by X-ray Diffraction Analysis, *Proc. 1st Nat. Conf. Clays and Clay Tech.*, Calif. Dept. Nat. Res., Bull. 169, 1955, p. 119; *X-ray Identification and Crystal Structure of Clay Minerals* (Miner. Soc., London), 1951.

R. E. Grim, *Clay Mineralogy* (McGraw Hill, New York), 1953.

INFRA-RED ABSORPTION

The infra-red spectrum of a mineral powder is a characteristic property and may be used for identification. The absorption of infra-red radiation depends on the fact that atoms in a mineral are in a constant state of vibration in frequencies which are of the same order of magnitude as those of infra-red radiation. Hence absorption occurs at frequencies corresponding to the intramolecular vibration frequencies.

Absorption is characteristic for certain molecular groupings within the mineral structure, and may therefore be used to indicate the presence of a certain arrangement of molecules, e.g. the OH group, bonded or unbonded. Infra-red absorption curves plotted with transmission as a function of wavelength or frequency, give absorption bands by which the principal groups of clay minerals can be recognized, but it is not yet possible to distinguish between members within a group. Data are available in the references cited below.

General References

H. Alder *et al.*, Infra-red Spectra of Reference Clay Minerals, *Amer. Petrol. Inst., Proj. 49, Rept. No. 8* (Columbia University, New York), 1950.

R. B. Barnes *et al.*, *Infra-red Spectroscopy* (Reinhold, New York), 1944.

A. M. Buswell and B. F. Dudenbostel, Spectroscopic Studies of Base Exchange Material, *Journ. Amer. Chem. Soc.*, **63**, 1941, p. 2554.

W. D. Keller and E. E. Pickett, Absorption of Infra-red Radiations by Clay Minerals, *Amer. Journ. Sci.*, **248**, 1950, p. 264.

P. G. Nahin, Infra-red Analysis of Clays and Related Minerals, *Proc. 1st Nat. Conf. Clays and Clay Tech.*, Calif. Dept. Nat. Res., Bull. 169, 1955, p. 112.

THE KAOLIN GROUP

The minerals in this group are hydrated aluminium silicates with some variation in arrangement of the structural units and amount of water. The structural units are the silicon tetrahedron and the aluminium octahedron, one layer of each being combined as the unit cell. The structure is known as the 1-1 layer lattice (Fig. 53).

The minerals in this group are: kaolinite, dickite, nacrite, the so-called 'fireclay mineral', halloysite ($4\text{H}_2\text{O}$), halloysite ($2\text{H}_2\text{O}$), anauxite and allophane (see also Ch. I, this volume, for detailed mineralogical data).

Kaolinite, dickite and nacrite are physically distinct minerals which can be readily recognized from optical properties and from differential thermal analyses. X-ray identification can also be made, although the basal spacing at about 7.2\AA is common to each of the three. The 'fireclay mineral' is a kaolinite with a disordered structure¹.

Halloysite ($4\text{H}_2\text{O}$) (endellite) and halloysite ($2\text{H}_2\text{O}$) (metahalloysite) vary in particle shape, water content and X-ray diffraction data. Anauxite is a silica-rich kaolinite² with an additional silica sheet between the layers; allophane is amorphous, or nearly so. There may possibly be a gradation between disordered kaolinite and allophane.

The relation between kaolinite and halloysite has been summarized by T. F. Bates as follows³:

Mineral	Randomness	Total water per half unit cell
Kaolinite	Shifts of nb 0/3 and random shifts parallel to b axis	
Halloysite ($2\text{H}_2\text{O}$)	Random shifts in both the a and b directions	2.5-2.7
Halloysite ($4\text{H}_2\text{O}$)	Random shifts in both the a and b directions	3.5-4.0
Allophane	Complete	

KAOLINITE

Structure. 1-1 layer lattice (Fig. 53).

Si-tetrahedron	$\left\{ \begin{array}{l} 6 \text{ O}^{-2} \\ 4 \text{ Si}^{+4} \end{array} \right.$	$\left\{ \begin{array}{l} -12 \\ +16 \end{array} \right.$	sum of charges
Al-octahedron	$\left\{ \begin{array}{l} 4 \text{ O}^{-2}, 2(\text{OH})^{-1} \\ 4 \text{ Al}^{+3} \\ 6(\text{OH})^{-1} \end{array} \right.$	$\left\{ \begin{array}{l} -10 \\ +12 \\ -6 \end{array} \right.$	$\left\{ \begin{array}{l} -28 \\ +28 \end{array} \right.$

¹ G. W. Brindley, *op. cit.*, 1951, p. 50.

² S. B. Hendricks, *Journ. Geol.*, 50, 1942, p. 276.

³ *Amer. Inst. Min. and Met. Eng.* (New York), 1952, p. 144.

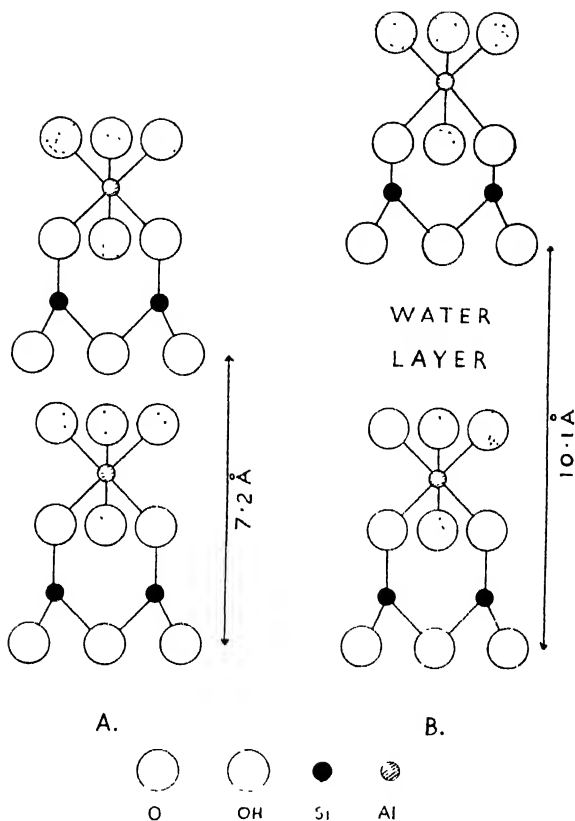


FIG. 53. Schematic representation of the arrangement of layers in A Kaolinite; B Halloysite (Hydrated). (Symbols for tons as in FIG. 50. A — angstrom unit.) (After G. W. Brindley. Courtesy The Mineralogical Society, London.)

X-ray Diffraction Data. Very strong basal reflections at about 7\AA (001) and 3.5\AA (002) are used in diagnosis. Complete lattice spacings, indices and intensities are given by G. W. Brindley¹. Chlorite also has a first order reflection at 7\AA , and in order to establish the identity of this line with certainty, it is necessary to treat the sample with HCl to remove the chlorite, and to heat to 600 C. at which temperature the kaolinite structure is destroyed².

Chemical Composition. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

Ion-Exchange Capacity. 3 to 15 m.e. per 100 g. at pH7. Exchange capacity varies with grain-size, due to presence of external O and OH ions (the lattice is balanced internally).

¹ *Op. cit.*, 1951, p. 71.

² G. W. Brindley, *op. cit.*, 1955, p. 120.

Reaction in Acid. Insoluble in HCl when well-crystallized, but varies with size of particles, acid concentration and ratio of mineral to acid.

Thermal Curves. The dehydration curve for kaolinite indicates a gradual loss in weight from about 400°C., with a sharp inflection at 520°C. when the hydroxyl water is removed¹.

Differential Thermal Analysis. There is a strong endothermic peak at 610–620°C., and a sharp exothermic peak at 980°C. The structure collapses on loss of water at the endothermic peak.

Optical Properties. $\alpha = 1.553\text{--}1.563$; $\gamma = 1.560\text{--}1.570$; $\gamma - \alpha = 0.006\text{--}0.007$; Opt. neg., $2V = 24^\circ\text{--}50^\circ$; dispersion $\rho > \nu$, weak; optic plane and $Z \perp$ to (010); $X \wedge \perp (001) = 3^\circ \pm$.

Shape. Aggregates of kaolinite crystals large enough for examination with the petrological microscope are vermicular in habit, with perfect basal cleavage. Electronmicrographs show that the plates are hexagonal in various states of perfection (Pl. 58).

Dye Adsorption. Many dyes are adsorbed by kaolinite and some produce artificial pleochroism, e.g. crystal violet, safranin-o or -y, and basic fuchsin².

Adsorption of Organic Molecules. Small exchange reaction.

Infra-red Absorption. Can be distinguished from micaceous clay minerals by position of absorption bands.

Occurrence. In soils subject to leaching at a low pH; in hydrothermally altered rocks; in weathering rocks.

General References

C. S. Ross and P. F. Kerr, The Kaolin Minerals, *U.S. Geol. Surv. Prof. Paper* 165-E, 1931.

T. F. Bates, Inter-relationships of Structure and Genesis in the Kaolin Group. Problems of Clay and Laterite Genesis, Symposium, *Amer. Inst. Min. and Metall. Eng.*, New York, 1952.

DICKITE

Structure. Similar to kaolinite, but the unit cell contains two kaolinite type layers.

X-ray Diffraction Data. First order basal spacing similar to that of kaolinite, but dickite can be distinguished from it by spacings in the range between 2.5 and 7.2 Å which differ in position and intensity from those in kaolinite³.

Chemical Composition. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

Ion-Exchange Capacity. Similar to kaolinite.

Reaction in Acid. Similar to kaolinite.

Thermal Curves. The dehydration curve for some dickites resembles that for kaolinite, but the larger crystals do not show an appreciable loss of water below 580°C., but complete loss at about 600°C.⁴

Differential Thermal Analysis. A strong endothermic peak at 700°C. and an exothermic peak similar to that of kaolinite at 980°–990°C.

¹ P. G. Nutting, *op. cit.*, 1943.

² G. T. Faust, *U.S. Bur. Mines Rept. Invest.*, 3522, 1940.

³ G. W. Brindley, *op. cit.*, 1951, p. 70, Table 11, 2.

⁴ P. G. Nutting, *op. cit.*, 1943.

Optical Properties. $\alpha = 1.560-1.561$; $\gamma = 1.566-1.567$; $\gamma - \alpha = 0.006$.

Biaxial positive, $2V = 52^\circ-80^\circ$; $Z = b$; $X \wedge c = +15^\circ-20^\circ$. Monoclinic with $\beta = 96^\circ 50'$.

Shape. Well-formed hexagonal crystals very often large enough for examination with the petrological microscope.

Dye Adsorption. Not strongly stained with dyes and not pleochroic.

Infra-red Adsorption. Similar to kaolinite except at 8.15μ .

Occurrence. Very often in veinlets associated with metallic minerals; as authigenic crystals in sandstones.

General References

C. S. Ross and P. F. Kerr, The Kaolin Minerals, *U.S. Geol. Surv., Prof. Paper*, 165-E, 1931.

F. Smithson, The Petrography of Dickitic Sandstones in North Wales and Northern England, with an Appendix on the Differentiation of Dickite and Kaolinite by G. Brown, *Geol. Mag.*, 91, 1954, p. 177.

NACRITE

Structure. Similar to that of kaolinite but the unit cell contains six kaolinite-type layers¹. The structure appears quite regular without random shifts of layers such as may be present in dickite. Nacrite is rather rare but forms well-developed single crystals.

X-ray Diffraction Data. Nacrite can be distinguished from both kaolinite and dickite by various spacings and their intensity, e.g. 7.08\AA (001), 3.58\AA (002), 2.418\AA (112), 2.93\AA (003)².

Chemical Composition. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

Ion-Exchange Capacity. Probably like kaolinite.

Reaction to Acid. Similar to kaolinite.

Thermal Curves. Dehydration is slower than in kaolinite and dickite. Loss of water on heating depends on fineness of grinding of the sample; ground to pass 180 mesh, loses most of its water between 400° and 500°C ., whereas coarser crystals lose the bulk of their water between 500° and 600°C . Definite breaks in the curves occur at about 650° and 750°C .³

Differential Thermal Analysis. Owing to small size of specimens, not very satisfactory. P. F. Kerr *et al.*⁴ give one curve for material from Augustusbourg, Saxony, which shows a long double endothermic peak starting at about 500°C . and ending just above 700°C ., the latter part being similar to that of dickite.

Optical Properties. Nacrite is almost orthorhombic with $\beta = 90^\circ 20' \pm 10'$. $\alpha = 1.557-1.560$; $\gamma = 1.563-1.566$; $\gamma - \alpha = 0.006$; biaxial neg.; $2V = 40^\circ$; $Z = b$; $X \wedge \perp (001) = 10^\circ-12^\circ$.

Shape. Wedge-shaped or fan-like plates, in aggregates.

Dye Adsorption. Not readily stained by dyes; not pleochroic.

¹ S. B. Hendricks, *Zeit. Krist.*, 100, 1938, p. 509.

² G. W. Brindley, *op. cit.*, 1951, p. 70, Table 11, 2.

³ O. von Knorring, G. W. Brindley and K. Hunter, *Miner. Mag.*, 29, 218, 1952, p. 963.

⁴ Differential Thermal Analyses of Reference Clay Mineral Specimens, *Amer. Pet. Inst. Proj.* 49, *Prel. Rep.* 3, 1949.

Infra-red Absorption. Like dickite, except for 10.73μ peak.

Occurrence. As a well-crystallized alteration product of feldspar in metallic mineral veins; in joints, cracks and small pockets in metamorphic rocks (Finland); in quartz veins in slickensided syenite (Leicestershire).

General References

C. S. Ross and P. F. Kerr, *op. cit.*

R. J. Firman, On the Occurrence of Nacrite at Shap, Westmorland, *Miner. Mag.*, **30**, 1953, p. 199.

G. W. Brindley and K. Hunter, The Thermal Reactions of Nacrite and the Formation of Metakaolin, Alumina and Mullite, *Miner. Mag.*, **30**, 1955, p. 574.

HALLOYSITE

Nomenclature. There are two forms of halloysite which differ in water content; the hydrated form is endellite (halloysite) and the dehydrated is halloysite (metahalloysite). To avoid confusion they are referred to as the $4\text{H}_2\text{O}$ and the $2\text{H}_2\text{O}$ forms respectively.

Structure. 1-1 layer lattice like kaolinite, but differs in an increase in randomness, the presence of interlayer water with an increase in the height of the unit cell and a change in morphology¹. The only order is in the parallelism of (001) planes and the regularity with which they are spaced in the direction of the c axis (see Fig. 53).

Chemical Composition. $(2\text{H}_2\text{O})$ Metahalloysite, $(\text{OH})_8\text{Si}_4\text{Al}_4\text{O}_{10}$. $(4\text{H}_2\text{O})$ Endellite, $(\text{OH})_8\text{Si}_4\text{Al}_4\text{O}_{10}$. $4\text{H}_2\text{O}$. The $4\text{H}_2\text{O}$ -form dehydrates irreversibly to the $2\text{H}_2\text{O}$ -form at about 400°C ., but variable amounts of water are lost at temperatures well below this.

Ion-Exchange Capacity. Halloysite $2\text{H}_2\text{O}$, 5-10 m.e. per 100 g. with exchange taking place as in kaolinite. Halloysite $4\text{H}_2\text{O}$, 40-50 m.e. per 100 g. with exchange positions within the lattice due to presence of the interlayer water.

Reaction in Acid. Appreciably soluble in 20% hot H_2SO_4 and in cold HCl; differs from kaolinite in this respect.

Thermal Curves. Gradual loss of water up to 400°C ., large loss of water between 400° and 530°C ., with a further gradual loss to 800°C .²

Differential Thermal Analysis. Endothermic and exothermic peaks occur at similar temperatures to those of kaolinite, but there are additional endothermic peaks for the $4\text{H}_2\text{O}$ -form at 135° - 160°C . and at 320° - 335°C . The endothermic peak at about 600°C . is asymmetrical. As the $4\text{H}_2\text{O}$ form dehydrates at low temperatures, humidity control is necessary.

X-ray Diffraction Data. Halloysite- $4\text{H}_2\text{O}$ has a strong 10.1\AA basal reflection which is reduced to about 7.4\AA when heated to 100°C . or placed in a dry atmosphere, or in vacuo. Halloysite- $2\text{H}_2\text{O}$ has broad basal reflections (001) and (002). The two-dimensional (hk) bands, especially the (02) band is quite characteristic with sharp low-angle

¹ T. F. Bates, *op. cit.*, 1952.

² P. G. Nutting, *op. cit.*, 1943.

termination and its intensity is greater than that of the basal reflections. The (001) spacing is 7.4 or 7.5 Å but after heating at 400°C. for half to one hour it is reduced to 7.2 Å and becomes much sharper.

Optical Properties. Much Halloysite is isotropic. $n = 1.526-1.532$ ($2\text{H}_2\text{O}$) and $n = 1.548-1.556$ ($4\text{H}_2\text{O}$). Birefringence very low.

Shape. Electronmicrographs show that Halloysite- $2\text{H}_2\text{O}$ is in the form of hollow tubes, many of which have split longitudinally or collapsed to form laths or ribbons¹. Endellite- $4\text{H}_2\text{O}$ probably has well-developed tubes which become strained and collapse on dehydration (Pl. 59).

Dye Adsorption. Similar to kaolinite².

Infra-red Absorption. Differs from kaolinite in 10.68μ band, weak absorption at 12.5μ .

Adsorption of Organic Molecules. Adsorption of highly polar molecules takes place between the unit layers (see discussion by R. E. Grim³).

Occurrence. Formed by weathering, particularly where oxidizing sulphides have supplied sulphuric acid. Moist conditions are necessary for preservation of endellite.

General References

- T. F. Bates, Inter-Relationships of Structure and Genesis in the Kaolinite Group. Problems of Clay and Laterite Genesis. Symposium, *Amer. Inst. Min. and Met. Eng.*, 1952.
 C. S. Ross and P. F. Kerr, Halloysite and Allophane, *U.S. Geol. Surv. Prof. Paper 185G*, 1934-5.
 A. Swineford, J. D. McNeal and C. F. Crumpton, Hydrated Halloysite in Blue Hill Shale, *Proc. 2nd Nat. Conf. Clays and Clay Minerals* (Pub. 327, Nat. Acad. Sci. Nat. Res. Council, Washington, D.C.), 1954, p. 158.

ANAXITE

Structure. Consists of double Si-tetrahedral sheets interlayered at random between kaolinite unit layers⁴. In the double silica units the tetrahedra of each sheet point towards the centre and a common O forms the tip of the tetrahedra in both sheets. This gives the following structure.

	Charge
6 O^{2-}	-12
4 Si^{4+}	+16
4 O^{2-}	-8
4 Si^{4+}	+16
6 O^{2-}	-12

X-ray Diffraction Data. Similar to kaolinite.

Chemical Composition. Apparently forms an isomorphous series with kaolinite; some samples contain excess of SiO_2 above that required for the kaolinite formula ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$).

¹ T. F. Bates, F. A. Hildebrand and A. Swineford, *Amer. Miner.*, **35**, 1950, p. 463.

² G. T. Faust, *op. cit.*, 1940.

³ *Op. cit.*, 1953, p. 252 and refs. cited.

⁴ S. B. Hendricks, *Journ. Geol.*, **50**, 1942, p. 276.

Ion-Exchange Capacity. No data, but probably similar to that of kaolinite.

Reaction in Acid. Slightly soluble.

Thermal Curves. Dehydration takes place at a lower temperature than in kaolinite; loss of water starts below 400°C.; the main dehydration is at about 430°C.; a slight loss continues to above 600°C.¹

Differential Thermal Analysis. Similar to kaolinite.

Optical Properties. Similar to kaolinite.

Shape. Similar to kaolinite.

Dye Adsorption. Similar to kaolinite.

Infra-red Absorption. Similar to kaolinite².

Occurrence. As for kaolinite.

General Reference

C. S. Ross and P. F. Kerr, *The Kaolin Minerals*, U.S. Geol. Surv., Prof. Paper 165-E, 1930.

ALLOPHANE

Structure. Completely random in all three unit cell dimensions.

X-ray Diffraction Data. Amorphous to X-rays; however, some more highly organized allophane has been reported³ in which diffuse bands occur at 3.5-3.0Å, 2.26-2.08Å, 1.45-1.27Å and 1.22-1.12Å.

Chemical Composition. $\text{Al}_2\text{O}_3 : \text{SiO}_2$, ranges from about 1 : 1 to 1 : 2 with $n\text{H}_2\text{O}$. Presence of P_2O_5 in some samples suggests admixture with evansite.

Ion-Exchange Capacity. About 70 m.e. per 100 g.⁴; due to unsatisfied bonds on poorly organized crystal structure.

Reaction in Acid. Gelatinizes with HCl.

Thermal Curves. Somewhat variable according to water content; some specimens show a regular loss of water up to about 500°C. and then a slight additional loss until over 800°C.

Differential Thermal Analysis. There is a large endothermic peak at 185°C. and a medium exothermic peak at 990°-995°C.

Optical Properties. $n = 1.468-1.512$.

Shape. No crystalline shape; may be rounded or quite irregular.

Dye Adsorption. No data.

Infra-red Absorption. Allophane is characterized by broad absorption between 800^{-1} cm. and 1225^{-1} cm. with a maximum at about 980^{-1} cm. Absorption is shown between 1500^{-1} cm. and 1700^{-1} cm. which is probably due to absorbed water. Absorption at 3300^{-1} cm. is also due to water. That allophane is not a microscopic mixture of amorphous SiO_2 and Al_2O_3 is shown by the nature of its absorption.

Occurrence. Often associated with halloysite; in soils developing from volcanic ash in New Zealand and Japan.

¹ P. G. Nutting, *op. cit.*, 1943.

² H. Adler *et al.*, *Amer. Pet. Inst., Proj. 49, Prel. Rep. 8*, 1950, p. 23.

³ W. A. White, *Amer. Min.*, 38, 1953, p. 634.

⁴ W. A. White, *ibid.*

General References

- C. S. Ross and P. F. Kerr, Halloysite and Allophane, *U.S. Geol. Surv., Prof. Paper* 185G, 1934-35.
 H. Adler, Infra-red Investigations of Clay and Related Minerals, *Amer. Pet. Inst., Proj.* 49, *Prel. Rep.* 8, 1950, p. 23.
 K. S. Birrell and M. Fieldes, Allophane in Volcanic Ash Soils, *Journ. Soil Sci.*, 3, 1952, p. 156.

CHAMOSITE

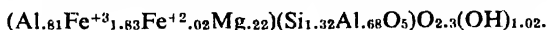
There are two structural types of chamosite, one like kaolinite, the other like chlorite. Chamosite is a hydrated ferrous silicate occurring in many iron ores; it has generally been classified as a chlorite. Within the kaolinite-type of chamosite, G. W. Brindley and R. F. Youell¹ identified two structural types, one with layers arranged in a monoclinic cell and therefore similar to that of a disordered kaolinite structure such as the 'fireclay' type, the other with layers arranged in an orthorhombic (pseudo-hexagonal) cell. There is in addition the chlorite type described by W. von Engelhardt².

Structure. Kaolinitic type of chamosite. The structure is similar to that of kaolinite of 'fireclay' type, *i.e.* disordered along the *b* axis with the layers randomly displaced by multiples of $b_0/3$. The layers are regularly arranged in the *c* direction. Within this type of chamosite there are two types of unit cell, orthorhombic and monoclinic. Chloritic type of chamosite. The unit cell is similar to that of chlorite, *i.e.* alternate mica-like and brucite-like layers. It is possible that the structure is disordered.

X-ray Diffraction Data. Kaolinitic type. Similar to kaolinite; a line of medium strength at about 2.67\AA which disappears after acid treatment, may indicate chamosite. It is probably not possible to differentiate a mixture of 20% chamosite, 60% kaolinite and 5% to 20% quartz³.

Chloritic type. This gives reflections at 14.0\AA (001), 7.05\AA (002) and 3.51\AA (004). There may be very weak intensity of the 14\AA reflection when the iron atoms are concentrated in the brucite layer.

Chemical Composition. Hydrated ferrous silicate, green in colour $(\text{Al}_{1.83}\text{Fe}^{+3}_{0.01}\text{Fe}^{+2}_{1.82}\text{Mg}^{+2}_{0.23})(\text{Si}_{1.32}\text{Al}_{0.68}\text{O}_5)(\text{OH})_{3.96}$. On heating to 300°C . a mixture of ferric and ferrous types is produced and at 400°C . the chamosite is a ferric chamosite with the following formula:



The chlorite-type chamosite:



Ion-Exchange Capacity. No data available, but probably low.

Reaction in Acid. Soluble in warm dilute acid.

Thermal Curves. The kaolinite type chamosite dehydrates at a temperature between 500° and 650°C ., passing through a ferric stage to

¹ *Miner. Mag.*, 30, 1953, p. 57.

² *Zeit. Krist.*, 104, 1942, p. 142.

³ G. W. Brindley, *Miner. Mag.*, 29, 1951, p. 502.

⁴ G. W. Brindley, *ibid.*

an amorphous one at about 500°C., but the chlorite type chamosite dehydrates in two stages as in chlorite.

Differential Thermal Analysis. The kaolinite type has a marked endothermic peak commencing at about 450°C., and having a maximum at about 550°C.¹ The ferric form does not have an endothermic peak as it is already dehydrated (see under *Chemical Composition*). The chlorite type chamosite has a similar D.T.A. curve to that of the chlorites, i.e. with two endothermic peaks at 550°C. to 600°C., and at about 800°C.; the latter is sometimes followed by an exothermic peak.

Optical Properties. Mean R.I. 1.62–1.66, kaolinite type². Moderate birefringence, optically negative.

Shape. Minute flakes, vermicules and ooliths. No electron microscope data.

Dye Adsorption. No data.

Infra-red Absorption. No data.

Occurrence. In iron ores of sedimentary origin, e.g. Northampton Sand Ironstone Formation and Clinton iron ores. In sideritic mudstones.

General Reference

G. W. Brindley and K. Robinson, X-ray Identification and Crystal Structures of Clay Minerals (*Miner. Soc., London*), Ch. 6, 1951.

THE MICACEOUS CLAY MINERALS

A number of clay minerals have the structure of mica (Fig. 54). These are hydrous mica (including illite), vermiculite, glauconite and celadonite. G. W. Brindley and D. M. C. MacEwan³ consider that there are no sharp lines of demarcation between micas proper, hydrous micas, montmorillonites and vermiculites. However, for descriptive purposes the hydrous micas are here distinguished from other clay micaceous minerals, and each treated separately. It was mentioned (p. 290) that the micas can be further divided into dioctahedral and trioctahedral groups. Muscovite, hydrous micas (illites), montmorillonites, glauconite and celadonite are dioctahedral; biotite and vermiculite are trioctahedral. In addition, many mixed layered minerals have been found, particularly in soil clays.

HYDROUS MICA (ILLITE)

Nomenclature. The terminology used here is that of G. Brown who suggested that hydrous mica be used to include all forms of clay mica, including illite; and that the latter, while still non-specific, be used for 'those clay micas which show no specific change of the 10Å reflection when subjected to mild thermal or chemical treatments'⁴.

¹ G. W. Brindley, *ibid.*

² J. H. Taylor, Petrology of the Northampton Sand Ironstone Formation, *Mem. Geol. Surv. Gt. Brit.*, 1949.

³ *Op. cit.*, 1953.

⁴ Nomenclature of the Mica Clay Minerals, X-Ray Identification and Structure of Clay Minerals (*Miner. Soc., London*), 1951, p. 155.

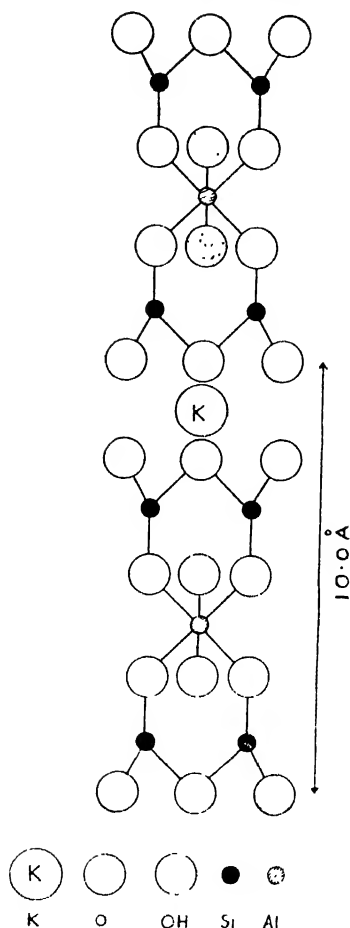


FIG. 54. Schematic representation of the arrangement of layers in mica (muscovite). (Symbols for ions as in FIG. 50. K potassium ion, Å -- angstrom unit.) (After G. W. Brindley, 1951. Courtesy The Mineralogical Society, London.)

Illite is the name proposed by R. E. Grim, R. M. Bray and W. F. Bradley¹ as a general term for the clay mineral of wide occurrence in argillaceous sediments and soils. It has been very extensively used in clay mineral literature. Recent work by H. S. Yoder and H. P. Engster² has shown that the Fithian illite and other illites are mixed-layer micas.

¹ *Amer. Min.*, **22**, 1937, p. 813.

² *Geochim. et Cosmochim. Acta.*, **8**, 1955, p. 249.

Structure. The arrangement of the atomic planes is similar to that of muscovite (Fig. 54), a 2-1 layer lattice, which is as follows:

	Interlayer K^{+1}	Charges	
Si-tetrahedron	$\left\{ \begin{array}{l} 6 O^{-2} \\ 3 Si^{+4}, 1 Al^{+3} \end{array} \right.$	$\left. \begin{array}{l} +1 \\ -12 \end{array} \right\}$	$\left. \begin{array}{l} \\ \\ \\ -44 \\ +42 \end{array} \right\}$
		$+15$	
Al-octahedron	$\left\{ \begin{array}{l} 4 O^{-2}, 2(OH, F)^{-1} \\ 4 Al^{+3} \end{array} \right.$	$\left. \begin{array}{l} -10 \\ +12 \end{array} \right\}$	
		-10	
Si-tetrahedron	$\left\{ \begin{array}{l} 3 Si^{+4}, 1 Al^{+3} \\ 6 O^{-2} \end{array} \right.$	$\left. \begin{array}{l} +15 \\ -12 \end{array} \right\}$	
	Interlayer K^{+1}	$+1$	

The excess of negative charge is neutralized by interlayer K ions which share their charges between adjacent layers, thus binding them together. The bond is strong enough in muscovite to prevent the entry of water molecules between lattice layers. Deficiency in K results in a negative charge. Theoretically isomorphous replacement could take place in both the silicon tetrahedron and the aluminium octahedron.

The hydrous micas differ from muscovite in a number of ways¹: there is less substitution of Al^{+3} for Si^{+4} , for in well-crystallized micas one-fourth of the Si^{+4} is replaced, whereas in the hydrous micas only about one-sixth is replaced. As a consequence of this smaller substitution, the silica: alumina ratio is higher and the net unbalanced charge deficiency is reduced from 2 per unit cell to about 1.3 per unit cell. The K ions between the unit layers may be partially replaced by other cations such as Ca^{+2} , Mg^{+2} and H^{+1} . There is some randomness in the stacking of the layers in the *c* direction.

X-ray Diffraction Data. The hydrous mica group minerals can be differentiated from other groups of clay minerals by the series of basal reflections from oriented aggregates. The (001) reflection is at about 10 Å and it is generally possible to identify an integral series of orders of this reflection. The reflections are not altered by heating to 500°C. or by glycerol saturation.

Chemical Composition. Muscovite (dioctahedral), $(OH)_1K_2(Si_6Al_2)Al_4O_{20}$; Biotite (trioctahedral), $(OH)_4K_2(Si_6Al_2)(Mg, Fe)_6O_{20}$. There are many polymorphic varieties². Chemical analyses given by R. E. Grim, W. F. Bradley and G. Brown³ show K_2O in muscovite to be 8.79% and in three samples of illite to be 6.56%, 6.93% and 6.90% respectively. The ignition loss for these illites is 7.88%, 6.82% and 7.49% respectively.

Ion-Exchange Capacity. The exchange capacity shows considerable variation in the range of 20 to 40 m.e. per 100 g. It is largely due to deficiency of K^{+} , also to substitution in the octahedral layer.

¹ R. E. Grim, *op. cit.*, 1953, p. 67.

² S. B. Hendricks and M. E. Jefferson, *Amer. Miner.*, 24, 1939, p. 729.

³ The Mica Clay Minerals, *X-ray Identification and Structure of Clay Minerals* (Miner. Soc., London), 1951, p. 138.

Reaction in Acid. Not changed by acid treatment.

Thermal Curves. Dehydration curves for illites¹ show a considerable water loss below 100°C., a gradual loss from 100°C. to about 350°C. a relatively abrupt large loss (OH lattice water) from 350°C. to about, 600°C. and a gradual loss above 600°C. A trioctahedral soil mica (derived from biotite) had a similar type of water loss².

Differential Thermal Analysis. Differential thermal curves show a small initial endothermic peak due to loss of adsorbed water; an endothermic reaction beginning at about 400° to 450°C., with a peak at about 500° to 600°C.; a small endothermic peak between 850° and 900°C., followed by a small exothermic peak.

Optical Properties. $\alpha = 1.54-1.63$; $\gamma = 1.57-1.67$; $\gamma - \alpha = 0.03-0.04$; negative, with 2 V small; X about \perp (001); some varieties are pleochroic. The appearance of the interference figure is a useful criterion in describing hydrous mica; when sharp and well defined it approximates to that of muscovite or biotite, but reduction in K and increase in H₂O cause diffuseness of the isogyres³.

Shape. Poorly defined flakes, irregular, but occasionally hexagonal (Pl. 60).

Dye Adsorption. p-amino phenol has been used to determine hydrous micas⁴.

Infra-red Absorption. Similar to that of montmorillonite.

Occurrence. Extremely common in soils, particularly of the temperate climates; in shales, limestones and other sedimentary rocks.

General Reference

- M. D. Foster, The Relation between 'Illite', Beidellite and Montmorillonite, *Proc. 2nd Nat. Conf. Clays and Clay Minerals* (Pub. 327, Nat. Acad. Sci., Nat. Res. Council, Washington, D.C.), 1954, p. 386.

GLAUCONITE (AND CELADONITE)

Structure. A dioctahedral mica with a charge deficiency in both tetrahedral and octahedral layers. The charges are balanced by inter-layer cations which are generally K⁺, but may be Ca⁺ or Na⁺. There is considerable replacement of Al¹³ by Fe⁺³, Fe⁺² and Mg⁺². The unit cell is composed of a single silicate layer rather than the double layer of many other dioctahedral micas⁵.

X-ray Diffraction Data. Similar to biotite but has a very weak second order basal spacing.

Chemical Composition. Glauconite: (K, Ca $\frac{1}{2}$, Na)_{0.84}(Al_{4.7}Fe¹³_{0.07}Fe⁺²_{0.19}Mg_{4.0})(Si_{3.65}Al_{0.35})O₁₀(OH)₂. Celadonite: (K, Ca $\frac{1}{2}$, Na)_{0.84}(Al_{3.34}Fe⁺³_{0.76}Fe⁺²_{0.24}Mg_{0.76})(Si_{3.89}Al_{0.10})O₁₀(OH)₂. S. B. Hendricks and C. S. Ross⁶. The interlayer cation does not amount to one equivalent.

Ion-Exchange Capacity. This is in the range for hydrous micas; often

¹ R. E. Grim, R. M. Bray and W. F. Bradley, *op. cit.*, 1937, p. 813.

² G. F. Walker, *Miner. Mag.*, 29, 1950, p. 72.

³ I. A. Dennison, W. H. Fry and P. L. Gile, Alteration of Muscovite and Biotite in the Soil, *U.S. Dept. Agric., Tech. Bull.* 128, 1929.

⁴ R. C. Mielenz and M. E. King, Identification of Clay Minerals by Staining Tests, *A.S.T.M. Proc.* 51, 1951, p. 1213.

⁵ S. B. Hendricks and C. S. Ross, *Amer. Min.*, 26, 1941, p. 683. ⁶ *Ibid.*

approximately 20 m.e. per 100 g. but may be only 11 m.e. per 100 g. Apparently completely reversible exchange between K, Na and Ca, which is the basis for its use as a water softener. Exchange reactions take place if glauconite is placed in heavy liquids, *e.g.* Clerici solution, the thallium ion entering the glauconite structure.

Reaction in Acid. Very appreciably soluble in 24% HCl and somewhat soluble in weaker acid. The ferric and ferrous iron is removed and glauconite is more than half dissolved¹.

Thermal Curves. Dehydration takes place gradually to about 700°C. At about 450° to 500°C. the dehydration rate is faster than at other temperatures².

Differential Thermal Analysis. Endothermic peaks occur at about 150°C., 590°C. and 990°C.

Optical Properties. $\alpha = 1.545-1.63$; $\gamma = 1.57-1.66$; $\gamma - \alpha = 0.025-0.030$. Biaxial negative; $2V = 0^\circ-20^\circ$. Pleochroic, yellow green. There is an increase of R.I. and birefringence with increase in Fe_2O_3 .

Shape. Rounded or irregular grains; encrusting and replacing other minerals. Electron micrographs show that glauconite has an appearance similar to that of illite.

Dye Adsorption. Dyes are adsorbed but the colour is masked by the strong green colour of the mineral.

Infra-red Absorption. No data, but probably similar to hydrous mica.

Occurrence. In marine sediments in suitable near-shore environments.

MONTMORILLONITE GROUP

Montmorillonite is a group name describing a number of related minerals all having the same crystalline structure. These minerals are sometimes referred to as montmorillinoids³. The study of the group has been greatly facilitated by the occurrence of very pure montmorillonites in the bentonites of the United States.

Structure. A 2-1 layer structure as in micas, but the layers are not held together by K^+ interlayer cations. There is a very weak bond between the units caused by the proximity of O layers and water; certain organic molecules can enter between the layers. The exchangeable cations are situated between the layers. Expansion takes place in the *c* direction with consequent variation in the basal spacing.

X-ray Diffraction Data. Basal reflections are variable and are changed by the presence of water layers which in turn are dependent on the exchangeable cation present. The following data are from I. Barshad⁴ and illustrate this point:

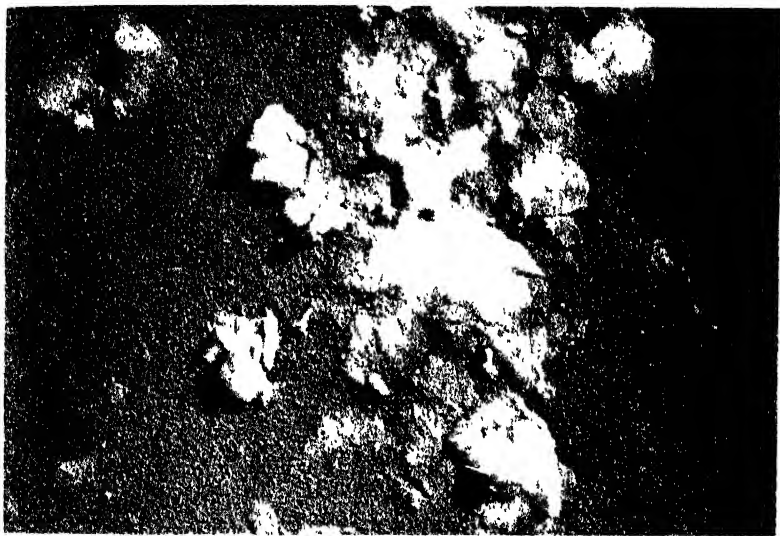
	Å	Å	Å	Å	Å	Å	Å	Å	Å	Å
Lattice spacings	14.5	14.8	15.1	13.4	12.9	11.9	12.0	12.1	12.3	12.9
Interlayer cation	H^+	Mg^{+2}	Ca^{+2}	Li^+	Ba^{+2}	Na^+	K^+	NH_4^+	Rb^+	Cs^+
Number of										
water layers	2	2	2	1	1	1	1	1	1	1

¹ C. O. Hutton and F. T. Seelye, *Amer. Min.*, 26, 1941, p. 599.

² P. G. Nutting, *op. cit.*, 1943.

³ D. M. C. MacEwan, *The Montmorillonite Minerals, X-ray Identification and Structure of Clay Minerals* (Miner. Soc., London), 1951.

⁴ *Amer. Min.*, 35, 1950, p. 225.



ELECTRON-MICROGRAPH OF MONTMORILLONITE GIENONITE
Kiowa Shale, Clark County, Kansas. Shadowed with Cr. at 18 16,000
Photo by Ada Swineford, State Geological Survey of Kansas



ELECTRON-MICROGRAPH OF ATTAPULGITE.

Gadsden County, Florida. Shadowed with Cr. at 14 28,000
Photo by Jane Armstrong, State Geological Survey of Kansas

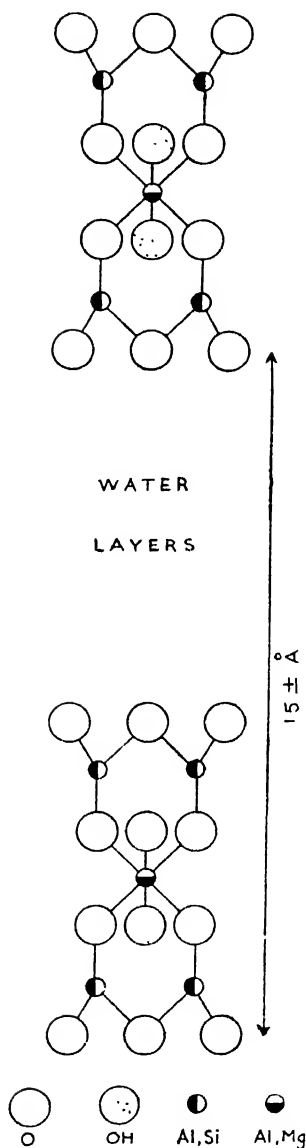
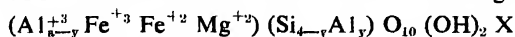


FIG. 55. Schematic representation of the arrangement of layers in montmorillonite (expanded). (Symbols for ions as in FIG. 50. Å = angstrom unit.) (After G. W. Brindley, 1951. Courtesy The Mineralogical Society, London.)

In identifying montmorillonite by X-ray diffraction, it is usual to convert the mineral to one form, *e.g.* to Ca-montmorillonite, by an exchange reaction and then to saturate with glycol or glycerol to expand the lattice. The resulting patterns have a high degree of regularity with sharp (001) lines. A sharp (001) reflection at 17\AA is usually obtained and is diagnostic, even in mixtures of clay minerals. Additional lines (hk) are unsymmetrical, invariable and due to interferences within the layers.

Chemical Composition. C. S. Ross and S. B. Hendricks¹ gave a generalized structural formula for the montmorillonite group of minerals:



(X = exchangeable cations).

They stressed the importance of ionic substitution in the montmorillonite structure, so that the charges on the lattice are unbalanced because of substitution of Mg^{+2} for Al^{+3} and Al^{+3} for Si^{+4} . This substitution may take place either in the octahedral or in the tetrahedral layer, or in both.

Members of the group differ chemically through isomorphous replacement and various minerals have been identified.

Structural formulae for certain minerals in the group are:—

Beidellite	$(\text{Al}_{1.46}^{+3} \text{Fe}_{0.6}^{+3} \text{Mg}_{0.6}^{+2}) (\text{Si}_{3.64} \text{Al}_{0.36}) \text{O}_{10} (\text{OH})_2$
Montmorillonite	$(\text{Al}_{1.65}^{+3} \text{Fe}_{0.9}^{+3} \text{Fe}_{0.2}^{+2} \text{Mg}_{0.25}^{+2}) (\text{Si}_{3.85} \text{Al}_{0.15}) \text{O}_{10} (\text{OH})_2$
Nontronite	$(\text{Fe}_{1.92}^{+3} \text{Fe}_{0.5}^{+2} \text{Mg}_{0.5}^{+2}) (\text{Si}_{3.51} \text{Al}_{0.49}) \text{O}_{10} (\text{OH})_2$
Volkhonskite	$(\text{Al}_{1.10}^{+3} \text{Fe}_{0.29}^{+3} \text{Cr}_{0.2}^{+3} \text{Fe}_{0.4}^{+2} \text{Ni}_{0.1}^{+2} \text{Mg}_{0.43}^{+2}) (\text{Si}_{3.44} \text{Al}_{0.46}) \text{O}_{10} (\text{OH})_2$
Hectorite	$(\text{Al}_{0.1}^{+3} \text{Li}_{0.6}^{+1} \text{Mg}_{0.67}^{+2}) (\text{Si}_4) \text{O}_{10} (\text{OH})_2$
Stevensite	$(\text{Mg}_{2.88}^{+2} \text{Fe}_{0.2}^{+3} \text{Mn}_{0.2}^{+3}) (\text{Si}_4) \text{O}_{10} (\text{OH})_2$
Sauconite	$(\text{Zn}_{2.40}^{+2} \text{Mg}_{1.8}^{+2} \text{Al}_{0.22}^{+3} \text{Fe}_{0.17}^{+3}) (\text{Si}_{3.47} \text{Al}_{0.53}) \text{O}_{10} (\text{OH})_2$
Saponite	$(\text{Mg}_{2.92}^{+2} \text{Fe}_{0.3}^{+3} \text{Fe}_{0.3}^{+2}) (\text{Si}_{3.40} \text{Al}_{0.60}) \text{O}_{10} (\text{OH})_2$

The montmorillonites fall into two sub-groups, dioctahedral (beidellite, montmorillonite, nontronite, and volkhonskite), and trioctahedral (hectorite, stevensite, sauconite and saponite).

C. S. Ross and S. B. Hendricks² from chemical analyses of numerous specimens of montmorillonite found that interpretation of these analyses could be simplified by a consideration of the crystal lattice structure. Silicon and aluminium have tetrahedral co-ordination with respect to oxygen, whereas ferric and ferrous iron, some aluminium, magnesium, lithium, chromium, manganic and manganous manganese and some other ions have octahedral co-ordination with oxygen. The exchangeable cations are situated on the surfaces of the silicate layers and their amounts are determined by the excess negative charge within the layer. See under Ion Exchange Capacity, p. 295.

Ion-Exchange Capacity. The exchange capacity is in the range of 70 to over 100 m.e. per 100 g., many samples having a figure of about 80 m.e. However, some members of the group have a very much

¹ *U.S. Geol. Surv., Prof. Paper* 205B, 1945.

² *Op. cit.*, 1945.

lower exchange capacity, notably stevensite, which has only 36 m.e. as reported by G. T. Faust and K. J. Murata¹. The exchange capacity varies with the amount of interlayer water present and the exchange-cation. Thus U. Hofmann and R. Klemen² found that for Ca-montmorillonite the exchange capacity was reduced from 93 to 41 m.e. per 100 g., by heating to 300°C., whereas the capacity of Na-montmorillonite was very little changed. The relationship of exchange capacity to various ions, to concentration of replacing solution and to ions in exchange positions, is not simple, but has been partially explained by C. E. Marshall³.

Reaction in Acid. Montmorillonites are appreciably soluble in HCl and the bases can be removed by digestion in hot 20% (6N) HCl for a few hours; in dilute acids (0.1%–0.4%) bases and silica go into solution in the same proportion as in the original clay; in pure water 36 p.p.m. of the original mineral dissolve, the portion in solution being richer in silica than the original mineral⁴. Digestion in 0.5N- and N-NaOH causes a breakdown of the structure to the extent of 7.5% and 11.6% respectively⁵.

Thermal Curves. Dehydration curves show that the inflection point between interlayer water and hydroxyl water is 300°C.

Differential Thermal Analysis. Endothermic peaks are found at 170°–190°C., 695°–730°C., and 885°–905°C. An exothermic peak occurs at 925°–935°C. In nontronite the endothermic peaks are at 200° and 500°C., and an exothermic peak at 870°C. In saucanite the endothermic peaks are at 178° and 289°C., 441°, 582° and 734°C.; exothermic peaks occur at 832° and 978°C. Saponite and stevensite give very similar D.T.A. curves, with endothermic peaks at 152°–159°C., 562° and 639°C., and 840° and 865°C.⁶.

Optical Properties.

Mineral	α	γ	$\gamma - \alpha$	Sign	2V	Other Properties
Montmorillonite	1.480	1.515	0.025–0.040	—	0°–30°	X about (001) pleochroic: yellow brown to green
Nontronite	1.590	1.630				
	1.565–	1.600–	0.035–0.040	—	mod.	
	1.600	1.640				
Hectorite	1.485	1.516	0.031	—	small	
Saponite	1.480	1.510	0.030–0.035	—	mod.	
	1.490	1.525				
	1.550	1.592	0.035–0.042	—	small	
Volkhonskite	1.575	1.615				
	1.551	1.585	0.034	—	small	

¹ *Amer. Min.*, **38**, 1953, p. 980.

² *Zeit. Anorg. Chem.*, **262**, 1950, p. 95.

³ *The Colloid Chemistry of the Silicate Minerals* (Academic Press, New York), 1949.

⁴ P. G. Nutting, *Journ. Wash. Acad. Sci.*, **22**, 1932, p. 261; *op. cit.*, 1943.

⁵ M. D. Foster, *Amer. Min.*, **38**, 1953, p. 994.

⁶ G. T. Faust and K. J. Murata, *Amer. Miner.*, **38**, 1953, p. 973.

It should be noted that the birefringence of the montmorillonite group minerals is of the same order as that of actinolite, diopside, olivine and tourmaline.

The technique for determination of refractive index of clay films is described by C. S. Ross and S. B. Hendricks¹, whence additional data may be obtained.

Shape. The montmorillonite group minerals occur in extremely small particles. Electronmicrographs show that montmorillonite (Pl. 61) is in aggregates of irregular flake-shaped units, whereas nontronite is lath-shaped or rod-like. Hectorite is in thin laths and sauconite is in much broader laths. Montmorillonites are the most difficult of the clay minerals to characterize morphologically, and to some extent the exchange cation influences the shape². Excellent illustrations have been made by T. F. Bates³.

Dye Adsorption. Staining readily produced by the technique described by G. T. Faust⁴. The staining hue of natural bentonites (montmorillonites) depends on their pH. It is possible to distinguish montmorillonite group minerals from kaolinite group minerals by staining.

Adsorption of Organic Molecules. The exchangeable cations may be replaced by large organic cations, amines and polyamines, which give rise to characteristic spacings between the montmorillonite layers⁵. The organic cations enter between the layers where they lie flat on the surface of the layers. S. B. Hendricks⁶ showed that the observed spacings between the layers are attributable to definite orientations of the large cations. W. F. Bradley⁷ and D. M. C. MacEwan⁸ showed that neutral molecules of fairly large size can also be strongly adsorbed by montmorillonite. These also form well-marked layers. For additional details, consult general references below.

Infra-red Absorption. The spectra recorded are similar to those for illite; nontronite has prominent 9.8μ and 12.25μ bands and hectorite has a 9.9μ band, which may be distinctive⁹.

Occurrence. C. S. Ross and S. B. Hendricks¹⁰ have summarized the occurrence of the montmorillonite group of minerals as follows: (1) in soils, either as essential minerals of the clay fraction or in association with other clay minerals; (2) as bentonites; (3) in pegmatite veins as an alteration product of other minerals; (4) in mineral veins, both as vein-minerals and as gouge-clays; (5) as one of the

¹ *Op. cit.*, 1945, p. 54.

² A. Mathieu-Sicaud, J. Mering and I. Perrin-Bonnet, *Bull. Soc. Franc. Minér.*, **74**, 1951, p. 439.

³ *Proc. 1st Nat. Conf. Clays and Clay Tech.*, Calif. Dept. Nat. Res. Bull. **169**, 1955, p. 130.

⁴ *Op. cit.*, 1940.

⁵ J. E. Gieseking, *Soil Sci.*, **47**, 1939, p. 1.

⁶ S. B. Hendricks, *Journ. Phys. Chem.*, **45**, 1941, p. 65.

⁷ *Journ. Amer. Chem. Soc.*, **67**, 1945, p. 975.

⁸ *Trans. Farad. Soc.*, **44**, 1949, p. 349.

⁹ P. G. Nahin, *op. cit.*, 1955.

¹⁰ *Op. cit.*, 1945, p. 60.

dominant minerals in water-laid shales. It will be shown later (p. 338) that montmorillonite in soils is dependent on environment and particularly on pH.

General References

- R. E. Grim, *Clay Mineralogy* (McGraw-Hill, New York), 1953.
 M. D. Foster, The Importance of the Exchangeable Magnesium and Cation-Exchange Capacity in the Study of Montmorillonitic Clays, *Amer. Min.*, **36**, 1951, p. 717.
 C. S. Ross, Sauconite—A Clay Mineral of the Montmorillonite Group, *Amer. Min.*, **31**, 1946, p. 411.
 C. S. Ross and S. B. Hendricks, Minerals of the Montmorillonite group, their Origin and Relation to Soils and Clays, *U.S. Geol. Surv., Prof. Paper* **205B**, 1945.

VERMICULITE

Vermiculite is a micaceous mineral which occurs in quite large plates in altered rocks and in a fine grained state in soils. The water content causes the plates to expand on heating. The expanded plates are refractory and have low specific gravity and low heat conductivity; they have many commercial uses. Vermiculite is a hydrothermally altered biotite, hence trioctahedral, brown or greenish brown in its natural state, but silvery white on heating. Vermiculite occurs in soils whose parent material contains biotite. It may be associated with montmorillonite, chlorite or hydrous mica. Soil vermiculite has not been completely studied and may not have the same properties as commercial vermiculite.

Structure. The vermiculite structure consists of sheets of trioctahedral mica or talc, separated by layers of water molecules occupying a definite space (4.98\AA), about the thickness of two water molecules.

$y\text{H}_2\text{O}$ double water layers

$x(\text{Mg}^{2+}, \text{Ca}^{2+})$	x^+
6O^{2-}	-12
$(4-x)\text{Si}^{4+}\text{Al}^{3+}$	$(16-x)^+$
$4 \text{O}^{2-}, 2(\text{OH})^-$	-10
$6(\text{Mg}, \text{Fe})^{2+}$	$+12$
$4 \text{O}^{2-}, 2(\text{OH})^-$	-10
$(4-x)\text{Si}^{4+}\text{Al}^{3+}$	$(16-x)^+$
6O^{2-}	-12
$x(\text{Mg}^{2+}, \text{Ca}^{2+})$	x^+

The structure is unbalanced, chiefly in substitutions of Al^{3+} for Si^{4+} , which may be partially balanced by other substitutions within the mica lattice; there is always a residual net charge deficiency of 1 to 1.4 per unit cell. This charge deficiency is satisfied by cations which occur between the mica layers and are largely exchangeable.

X-ray Diffraction Data. A strong 14\AA reflection is diagnostic; this reflection loses its intensity at 500°C ., and a stronger 9.3\AA reflection appears. At 700°C . the diffraction pattern is similar to that of talc. Vermiculite can be distinguished from chlorite, whose diffraction pattern is similar, by heating at 700°C . for several hours. The chlorite

reflection at 14\AA persists, but that of vermiculite is replaced by a 9.3\AA reflection, as noted above¹.

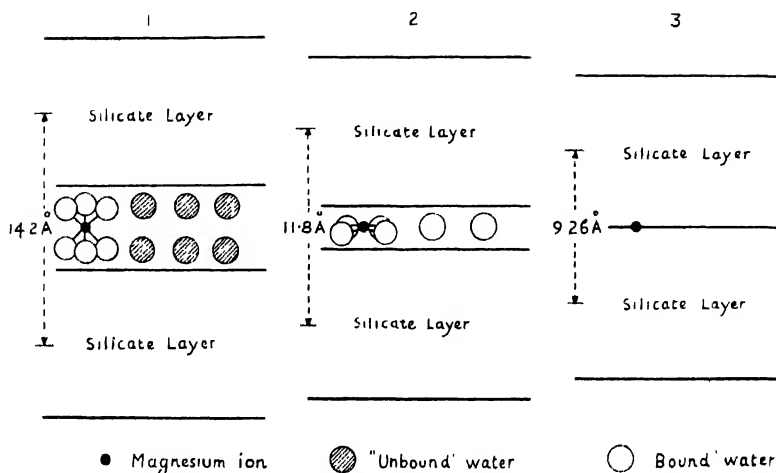


FIG. 56. Arrangement of the water layers in vermiculite (diagrammatic). 1, fully hydrated; 2, about half hydrated after removal of the 'unbound' water; 3, fully dehydrated with magnesium ion in hole in the silicate layer. In stage 2 only four water molecules are in contact with the magnesium ion.

(\AA = angstrom unit.)

(After G. F. Walker, 1951. Courtesy The Mineralogical Society, London.)

Chemical Composition. J. W. Gruner² gives the composition as $22\text{Mg} \cdot 5\text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3 \cdot 22\text{SiO}_2 \cdot 4\text{OH}_2\text{O}$, or $(\text{OH})_2(\text{Mg}, \text{Fe})_3(\text{Si}, \text{Al}, \text{Fe})_4\text{O}_{10}4\text{H}_2\text{O}$.

Ion-Exchange Capacity. The ion-exchange capacity is 100 to 150 m.e. per 100 g. and is related to the nature of the interlayer water. The charged layer is balanced by Mg^{2+} ion between the layers. This ion is surrounded by 6 water molecules ('bound' water) and there are also 8 'unbound' water molecules. The exchangeable ion is Mg^{2+} and also Ca^{2+} .³

Reaction in Acid. Some acids cause exfoliation and breakdown of stacking of the layers. H_2O_2 also acts in this way⁴. G. F. Walker⁵ gives a three-way test which consists in leaching with an ammonium salt solution (NH_4NO_3) or boiling gently in such a solution for a few

¹ G. F. Walker, *Vermiculite and Some Related Mixed-Layer Minerals, X-ray Identification and Structure of Clay Minerals* (Miner. Soc., London), 1951.

² *Amer. Min.*, **19**, 1934, p. 557.

³ I. Barshad, *Amer. Min.*, **33**, 1948, p. 655.

⁴ M. Drosdoff and E. F. Miles, *Soil Sci.*, **46**, 1938, p. 391.

⁵ *Miner. Mag.*, **28**, 1949, p. 693.

minutes, saturating with glycerol, and heat treatment for identification of vermiculite.

Thermal Curves. The dehydration curve¹ shows a large water loss below about 100°C. and a gradual loss from this temperature to about 850°C. G. F. Walker² shows that water is lost in three steps: below 100°C., from 250°C. to 400°C., and from 600°C. to 850°C. The (OH) lattice water is lost gradually from about 500°C. to 850°C. Exfoliation is due to abrupt heating at about 300°C.; slow heating does not produce exfoliation.

Differential Thermal Analysis. Natural vermiculites have a large dual, initial endothermic reaction with a peak at about 150°C. to 200°C., immediately followed by a smaller peak at about 250°C. to 275°C. There is a slight endothermic reaction between 700°C. and 800°C., and an exothermic reaction just above 800°C. The form of the curve is dependent on the replacing cations³.

Optical Properties. $\alpha = 1.525-1.561$; $\gamma = 1.545-1.561$; $\gamma - \alpha = 0.020-0.037$. Perfect basal cleavage; negative biaxial figure with very small 2V; X normal to (001); pleochroic, X = colourless; Y and Z = pale brown or pale green.

Shape. Large plates are irregular. No data are available on electron-micrographs, but vermiculite probably has a similar shape to hydrous mica (illite).

Dye Adsorption. A combination of dyes can be used to differentiate between illites, vermiculites and palygorskite (attapulgitite) but experience is necessary⁴.

Infra-red Absorption. No data.

Adsorption of Organic Molecules. Interlayer water is displaced by organic molecules and complexes are formed with organic ions. The amount of displacement of the basal reflection depends on the concentration as well as the nature of the organic ion⁵. Mg-, Ca-, Ba-, H-, Li- and Na-vermiculites take up a single layer of glycol molecules with a *c* axis spacing⁶ of 14.3 Å. For additional details see R. E. Grim⁷.

Occurrence. As noted above.

CHLORITE GROUP

The chlorite group minerals are common to many rocks, particularly schistose rocks, *e.g.* regionally metamorphosed sediments, or basic igneous rocks (chlorite schists). Fine-grained chlorites are also found in the clay fraction of soils, where they may be associated with vermiculite or hydrous mica.

Structure. In the chlorites the structure consists of alternate mica-like and brucite-like layers. The mica-like layers are trioctahedral with

¹ P. G. Nutting, *op. cit.*, 1943.

² *Miner. Mag.*, **29**, 1950, p. 72.

³ I. Barshad, *op. cit.*, 1948.

⁴ R. C. Mielenz and M. E. King, *A.S.T.M., Proc.* **51**, 1951, p. 1213.

⁵ G. F. Walker, *op. cit.*, 1951.

⁶ I. Barshad, *Amer. Min.*, **35**, 1950, p. 225.

⁷ *Op. cit.*, 1953, p. 263.

the general composition $(\text{OH})_4(\text{Si}, \text{Al})_8(\text{Mg}, \text{Fe})_6\text{O}_{20}$ and the brucite-like layers are $(\text{Mg}, \text{Al})_6(\text{OH})_{12}$. The mica layer is unbalanced by substitution of Al^{+3} for Si^{+4} and this deficiency of charge is balanced by an excess charge in the brucite sheet as a consequence of substitution of Al^{+3} for Mg^{+2} . The charge distribution in the layers is as follows, where $x = 1$ or 2 :

6 OH^{-1}	-6
$(6-2x)\text{Mg}^{+2}2x\text{Al}^{+3}$	$2(6-2x) + 3(2x)^+$
6 OH^{-1}	-6
6 O^{-2}	-12
$(4-x)\text{Si}^{+4}x\text{Al}^{+3}$	$4(4-x) + 3x^+$
4 $\text{O}^{-2}2(\text{OH})^{-1}$	-10
6 R(trioctahedral, R = Mg ⁺² , Mn ⁺² , Fe ⁺² , Fe ⁺³ , Cr ⁺³ , Ti ⁺⁴)	+12
4 $\text{O}^{-2}2(\text{OH})^{-1}$	-10
$(4-x)\text{Si}^{+4}x\text{Al}^{+3}$	$4(4-x) + 3x^+$
6 O^{-2}	-12

Isomorphous replacement produces a variety of chemically different chlorites.

X-ray Diffraction Data. The chlorites have a strong basal reflection at about 14\AA , which is similar to that of the montmorillonites and vermiculites, and a reflection at about 7\AA similar to that of kaolinite. On heat treatment to $400^\circ\text{--}500^\circ\text{C}$., the 14\AA line of montmorillonite collapses to $9.5\text{\AA}\text{--}10.5\text{\AA}$ (depending on the interlayer cations); further heating to $600^\circ\text{--}700^\circ\text{C}$. causes partial dehydration of chlorite and the 14\AA spacing is increased in intensity. If the 7\AA persists after heating to 600°C ., it belongs to chlorite, not to kaolinite.

Chemical Composition. Hydrous silicates of aluminium and magnesium with ferric and ferrous iron. Many different species (for details see A. N. Winchell¹, G. W. Brindley and K. Robinson²).

Ion-Exchange Capacity. No detailed information on the cation exchange capacity of chlorites, but it is assumed that it falls into the range 10-40 m.e. per 100 g.³

Reaction in Acid. Soluble in warm dilute HCl.

Thermal Curves. Dehydration takes place gradually to about 520°C ., when there is a sudden loss of water to about 570°C ., after which the loss is gradual to about $850^\circ\text{C}\text{--}900^\circ\text{C}$., when dehydration is complete⁴.

Differential Thermal Analysis. Generally two endothermic peaks are observed, one at about $550^\circ\text{C}\text{--}600^\circ\text{C}$., and a second at about 800°C .; there may be an exothermic peak just above 800°C .⁵

¹ *Amer. Min.*, **21**, 1936, p. 642.

² The Chlorite Minerals, *X-ray Identification and Structures of Clay Minerals* (Miner. Soc., London), 1951.

³ R. E. Grim, *op. cit.*, 1953, p. 129.

⁴ P. G. Nutting, *op. cit.*, 1943; S. Z. Ali and G. W. Brindley, *Proc. Leeds Phil. Soc.*, **5**, 1948, p. 109.

⁵ J. Orceel, *Bull. Soc. Franc. Miner.*, **50**, 1927, p. 75.

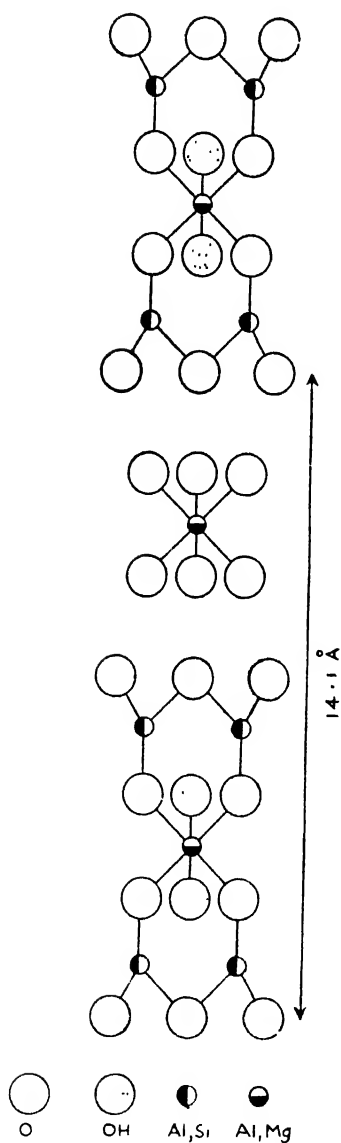


FIG. 57. Schematic representation of the arrangement of layers in chlorite. (Symbols for ions as in FIG. 50. Å = angstrom unit.) (After G. W. Brindley, 1951. Courtesy The Mineralogical Society, London.)

Optical Properties. There is much information on the optical properties of the various members of the chlorite group. Members can be classified by refractive index, birefringence and optic sign¹. For further details see under clinocllore, delessite, penninite, Ch. I, this volume.

Shape. Probably similar to hydrous mica. No electron microscope data.

Dye Adsorption. No data.

Infra-red Absorption. No data.

Adsorption of Organic Molecules. Swelling chlorite has been recorded by D. B. Honeyborne² and I. Stephen and D. M. C. MacEwan³. The spacings developed on glycerol treatment were within the range 14Å to 18Å and similar to those found in vermiculite.

Occurrence. As noted above.

General References

G. W. Brindley and S. Z. Ali, Thermal Transformations in Magnesian Chlorites, *Acta Crystall.*, 3, 1950, p. 25.

G. F. Walker, Distinction of Vermiculite, Chlorite and Montmorillonite in Clays, *Nature*, 164, 1949, p. 577.

MIXED-LAYER CLAY MINERALS

The descriptions and data presented in this chapter have been obtained by examination of pure specimens of these minerals, but in weathering products, in soils, and in recent sediments, it has been found that X-ray diffraction and other properties of the clay minerals are due to an interstratification of one type of layer with another. As stated by D. M. C. MacEwan¹, 'The layers may be either of different structural types, e.g. kaolinite or montmorillonite, or may consist of layers of the same structural type but with different thickness of interlamellar material, water or organic molecules, e.g. partially hydrated halloysite, partially expanded montmorillonite, chlorite and swelling chlorite'.

Mixed-layer structures are of two principal types, random and regular interstratification. In random stratification there is no uniform repetition of the layers. G. Brown and D. M. C. MacEwan⁵ have summarized the information on these types of clay minerals. They find that the most usual type of occurrence is caused by the existence of layers with two different degrees of hydration, e.g. a mixture of mica-type layers with montmorillonite or vermiculite-type layers, or of two successive montmorillonite hydrates or of brucite-like layers mixed with mica-type layers or layers of water molecules.

The procedure for identification of these random structures is given by those authors⁶.

¹ A. N. Winchell, *Amer. Min.*, 21, 1936, p. 642; G. W. Brindley and K. Robinson, *op. cit.*, 1951, p. 176.

² *Clay Min. Bull.*, 1, 1951, p. 150.

³ *Clay Min. Bull.*, 1, 1951, p. 157.

⁴ Discussion in G. W. Brindley, *Calif. Dept. Nat. Res., Bull.* 169, 1955, p. 127.

⁵ X-ray Diffraction by Structures with Random Interstratification, *X-ray Identification and Crystal Structures of Clay Minerals* (Miner. Soc., London), 1951, p. 266.

⁶ *Op. cit.*, 1951, p. 279.

As information accumulates from examination of the minus 2μ fractions of soils and recent sediments, it is evident that mixed-layering is of frequent occurrence. It may later be found that some regularly interstratified clay minerals merit specific names. For additional information references should be made to G. W. Brindley¹ and to the general references below.

General References

- W. F. Bradley, Analysis of Mixed-Layer Mineral Structures, *Anal. Chem.*, **25**, 1953, p. 727.
 G. Brown and D. M. C. MacEwan, The Interpretation of X-ray Diagrams of Soil Clays, 11, Structures with Random Interstratification, *Journ. Soil Sci.*, **1**, 1950, p. 239.
 J. Méring, L'interférence des Rayons X dans les Systèmes à Stratification Désordonnée, *Acta Cryst.*, **2**, 1949, p. 371; Les Reflexions des Rayons X par les Minéraux Argileux Interstratifiés, *4th Inter. Cong. Soil Sci.*, **3**, 1950, p. 21.

PALYGORSKITE (ATTAPULGITE) AND SEPIOLITE

The name palygorskite is used for the sepiolite-attapulgitic isomorphous series which includes a hydrous magnesium silicate end-member, sepiolite, and an assumed hydrous aluminium silicate end-member, paramontmorillonite². Attapulgitic is the name given to the Fuller's earth from Attapulgis, Georgia, and from Mormoiron, France, by J. de Lapparent³. The group is structurally related to the amphiboles.

Structure. The structure is similar to that of the amphiboles with long double chains of composition Si_4O_{11} which run parallel to the length of the fibres⁴. Silicon atoms associated with the oxygen sheets form long strips, each an amphibole unit wide. There are channels about one amphibole unit wide, and one brucite unit high which run parallel to the fibre, i.e. about 3.7\AA by 6.0\AA . These channels contain water but the structure does not collapse on dehydration and is therefore similar to that of certain of the zeolites.

X-ray Diffraction Data. Attapulgitic. There are prominent reflections at 10.50\AA and 3.23\AA and at 2.55\AA - 2.61\AA . At about 400°C . there is a water loss of about 6%, which is marked by a rapid contraction of the crystal lattice normal to the length of the fibre. This remains stable to about 775°C . Above 400°C ., the spacing at 10.5\AA becomes diffuse and other lines are also modified.

Sepiolite. Prominent reflections occur at 12.15\AA , 4.60\AA . On heating to 350°C . the strong 12.1\AA reflection becomes weak and diffuse and a new line appears at 9.8\AA .

Chemical Composition. The ideal formula for the magnesium end-member is: $(\text{OH}_2)_4(\text{OH})_2\text{Mg}_5\text{Si}_{10}\text{O}_{20} \cdot 4\text{H}_2\text{O}$ ⁵. It is not considered possible from the structure that a completely aluminous end-member

¹ *Op. cit.*, 1955, p. 120.

² P. F. Kerr, Clay Mineral Standards. *Amer. Petrol. Inst. Proj.* 49, 1949.

³ *Compt. Rendu.*, **202**, 1935, p. 1278.

⁴ W. F. Bradley, *Amer. Min.*, **25**, 1940, p. 405.

⁵ W. F. Bradley, *ibid.*

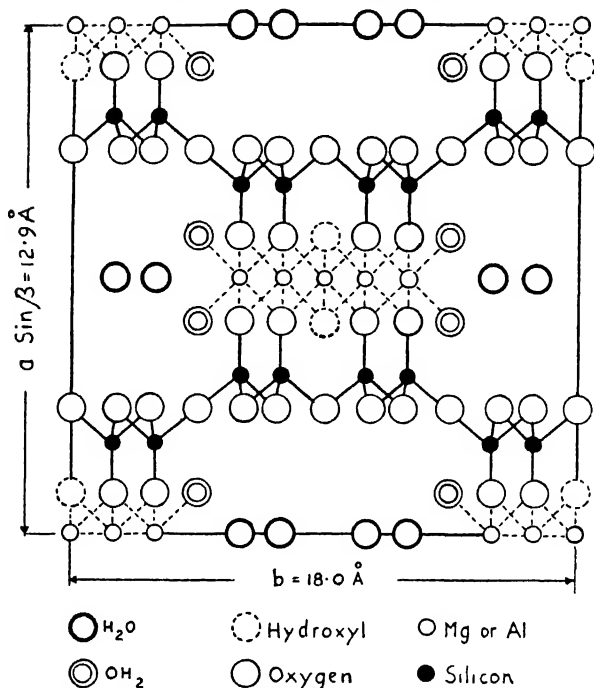


FIG. 58. The structural arrangement of Attapulgite (\AA - angstrom unit). (After W. F. Bradley, 1940. Courtesy of the author and The American Mineralogist.)

could exist. The attapulgite from Georgia contains 8.76% Al_2O_3 and 9.05% MgO .

Ion-Exchange Capacity. The exchange capacity of the mineral from Attapulgus, Ga., is 22 m.e. per 100 g¹. The exchange cations are held by ionic replacements in the lattice. There is no increase of exchange capacity with decrease in particle size.

Reaction in Acid. Sepiolite kept at boiling point in N/4 H_2SO_4 for 20 minutes is completely destroyed². Palygorskite is attacked by similar treatment but not destroyed after three hours.

Thermal Curves. Sepiolite shows loss of water in three steps, 50–100°C., at about 300°C., and at about 850°C. In palygorskite the loss of water is somewhat variable for specimens from different localities. Some have an inflection point at about 250°C., others at about 450°C.

¹ C. E. Marshall and O. G. Caldwell, *Journ. Phys. Coll. Chem.*, **51**, 1947, p. 311.

² S. Callière, *Sepiolite, X-ray Identification and Structures of Clay Minerals* (Miner. Soc., London), Ch. VIII, 1951.

Differential Thermal Analysis. Sepiolite has an endothermic peak commencing at 150°C., small endothermic peaks at about 440°C., and 750°C. There is a small exothermic effect at about 800°C. In attapulgite there are four endothermic peaks commencing at about 150°C., 350°C., 500°C. and 800°C., followed by an exothermic peak between 800° and 1000°C¹.

Optical Properties. Attapulgite. R.I. = 1.540; birefringence, 0.032; 2V small. C. E. Marshall and O. G. Caldwell² report variation in mean R.I. with water content of attapulgite films to be 1.51 for completely hydrated, and 1.54 for completely dehydrated mineral. Such films can be used to determine the water content at different temperatures.

Sepiolite. Mean R.I. 1.49; this increases to 1.54 when dehydrated above about 465°C³. Optic axial angle is variable; biaxial negative.

Shape. Electronmicrographs show that attapulgite is lath-like, but not hollow like halloysite (Pl. 62). R. E. Grim states⁴ that the maximum length is 4–5 μ and maximum thickness of 50Å to 100 Å.

Dye Adsorption. Will adsorb dyes, but it requires experience to differentiate attapulgite from hydrous micas and vermiculites⁵.

Infra-red Absorption. Gives a characteristic spectrum⁶.

Occurrence. Derived from montmorillonite and amphiboles and pyroxenes under special conditions.

General References

- S. Callière and S. Henin, Palygorskite-Attapulgite, *X-ray Identification and Crystall Structures of Clay Minerals* (Miner. Soc., London), Ch. IX, 1951.
- P. F. Kerr and P. K. Hamilton, Glossary of Clay Mineral Names, *Amer. Pet. Inst., Prelim. Report 1*, 1949.

MINERALS ASSOCIATED WITH THE CLAY MINERALS

Almost any mineral may be associated with any clay mineral, but the principal ones are quartz, various iron oxides (generally hydrated), the aluminium oxides such as gibbsite and boehmite, cristobalite, phosphates, titanium oxides, maghemite, etc. D. M. C. MacEwan⁷ lists in addition pyrophyllite, talc, gypsum, feldspars, calcite, dolomite, magnesite, rhodochrosite, siderite, aragonite and apatite. These minerals will not be described here, but some will be mentioned in connexion with certain soil and clay types. Details of nearly all of them are to be found in Ch. I, this volume. X-ray data are given on the A.S.T.M. reference cards.

The Iron Oxides. Various minerals such as goethite, hematite, lepidocrocite, are very often present in clay materials, particularly in soil colloids. In general they reflect the environment in which the clay

¹ *Ibid.*

² *Op. cit.*, 1947.

³ S. Callière, *ibid.*

⁴ *Op. cit.*, 1953, p. 122.

⁵ R. C. Mielenz and M. E. King, *op. cit.*, 1951.

⁶ J. M. Hunt, *Amer. Pet. Inst. Rept. 49, Reel. Rep. 9*, 1950, p. 105.

⁷ *Ibid.*

mineral was formed, particularly with regard to the oxidation reduction processes. Free iron oxides occur in many soils, particularly those containing kaolinite, with which they are intimately associated as films on the micelle surfaces, as described by J. J. Fripiat and M. C. Gastuche¹. Maghemite, a magnetic hematite (Fe_2O_3) is fairly commonly associated with other weathering products in laterites² where its presence is thought to be an indication of tropical weathering conditions.

The Aluminium Oxides. Gibbsite is often present in the first stages of weathering of crystalline rocks under warm moist conditions. It very often accompanies kaolinite in laterites and lateritic soils. A useful test for the presence of gibbsite is staining with alizarin red-S³. Diaspore and boehmite have been found in some sedimentary clays.

The Titanium Oxides. Small quantities of anatase are of common occurrence in clay deposits. Amorphous titanium oxide (hydrated) is liable to occur in laterites developing from basic rocks as, for example, the Hawaiian basalts.

Cristobalite very often occurs in bentonites from the western United States, as does gypsum and sometimes calcite. *Zeolites* with clay minerals have been recorded from some formations, e.g. Popo Agie member of the Chugwater (Triassic), Wyoming. *Wavellite* is reported as a minor constituent of certain soils in Florida by R. S. Dyal⁴; it has developed from alumina from the breakdown of kaolinite and phosphate from phosphatic sands.

OCCURRENCE OF CLAY MINERALS

It was mentioned in the Introduction that clay minerals are of very widespread occurrence in the earth's crust; where sufficiently concentrated and free from an excess of non-clay minerals, they constitute commercial deposits. Such clay deposits will not be described here, but reference will be made to some types.

The clay minerals are, peculiarly sensitive to environment. In soils the micro-environment, coupled with the chemical composition of the weathering rock, determines development of any particular clay mineral and in the soil profile certain changes may take place. Thus certain rock types, climates and environments will determine what clay minerals will become available for transportation and deposition in sediments.

Alluvial soils contain clay minerals derived from erosion of soil profiles, or of rocks if the erosion is rapid, within the drainage area. Some clay minerals will be transported away from the drainage area and the distance that they travel will depend on their stability

¹ Étude Physico-chimique des Surfaces des Argiles, *Pub. L'inst. Nat. L'étude Agron. Congo Belg., Serie Scient.* **54**, 1952, p. 60.

² V. A. Eyles, *Mem. Geol. Surv.*, 1952, p. 85.

³ F. Hardy and G. Rodrigues, *Soil Sci.*, **48**, 1939, p. 361.

⁴ *Soil Sci.*, **17**, 1953, p. 55.

or resistance to change. Thus it was found that kaolinite and montmorillonite decreased towards the mouth of the Neuse River, which drains across the Piedmont and coastal plain in North Carolina¹, its place being taken by amorphous material, 'chlorite' and mixed-layer minerals. The clay minerals in the Mississippi River are dependent to a certain extent on the terrain which is drained, streams from the west carrying more montmorillonite than those from the east, which carry a higher percentage of illite².

Drainage basins in moist tropical regions will contribute to the rivers kaolinite together with silica and iron in solution. In regions where soil-forming processes are not as active as in the tropics, e.g. Scotland³, hydrous mica will be the principal clay mineral available for transportation. In glaciated regions comminuted rock will be transported instead of clay minerals.

CLAY MINERALS IN SOILS

As a consequence of weathering, rocks disintegrate by chemical and physical reactions into materials which are then susceptible to soil-forming processes. No hard and fast line of demarcation exists between rock weathering and soil formation. The factors of soil formation and the concept of a soil profile are described in Ch. VII, this volume, and will not be repeated here.

In the genesis of clay minerals in soils there are three important factors: (1) the chemical composition of the parent rock and its porosity. Minerals which can alter into clay minerals must be present, e.g. feldspars and ferromagnesian minerals. A pure quartzite contains nothing which can be changed into clay minerals, whereas a basalt is composed entirely of weatherable minerals; (2) the drainage of the area in which a weathering rock is situated; this, together with the porosity of the rock, permits or prevents the movement of water whereby changes in mineralogy can take place; and (3) the climate, cold, temperate or tropical; continuously or discontinuously moist or dry. In addition there is another important factor to be considered and that is the case of weathering of the rocks. Shales and allied types of rocks which already contain clay minerals in a fine state of subdivision, will pass these on to the newly developing soil, but the feldspars in a granite have first to be altered to a clay mineral before soil formation can be initiated.

These factors make up the environment of clay mineral genesis in soils and it takes but little imagination to realize that there are infinite possible variations of this environment, although certain general patterns emerge.

¹ C. Q. Brown and R. L. Ingram, *Journ. Sed. Pet.* **24**, 1954, p. 196.

² R. S. Holmes and W. E. Hearn, *U.S. Dept. Agric., Tech. Bull.*, **833**, 1942.

³ W. A. Mitchell, *Journ. Soil Sci.*, **6**, 1955, p. 94.

The soil-forming processes are most active in warm, moist climates and least active in cold climates, where the ground is frozen for considerable periods each year. The amount as well as the type of clay mineral changes from the cold to the warm climate, as pointed out by H. Jenny and R. C. MacKenzie¹ (Figs. 59, 60). There is a progressive increase in the amount of clay minerals in soils towards the tropics and a progressive simplification

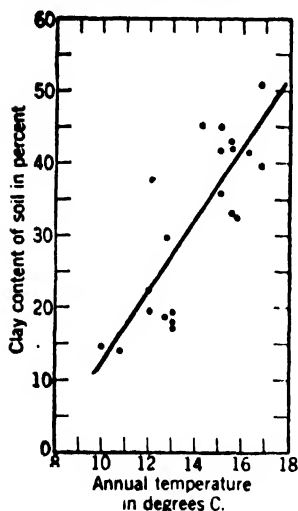


FIG. 59. The average clay content of soils derived from basic igneous rock increases from north to south in the Northern Hemisphere (data from eastern United States).

From H. Jenny, 1950. Courtesy John Wiley & Sons, Inc., New York.

towards a monomineralic clay, with kaolinite increasing, usually accompanied by various iron oxides.

Soil scientists have recognized that soils may be classified broadly into what are known as Great Soil Groups which have a world-wide distribution. The fact that the Great Soil Groups have been recognized is because there is a similarity of the end-products of development under conditions which can be evaluated in terms of equilibrium states; these are expressions of profile development with respect to organic matter, free oxides (Fe and Al), percentage base saturation, structure, colour, clay formation, mineralogical and chemical composition of the clay fraction². Thus a podzol in Australia, England, Russia, United States, or elsewhere, has the same kind of profile, which is a consequence of its having been developed by similar soil-forming factors. Such a classification simplifies and clarifies the genesis of clay minerals in soils.

Probably the most significant part of this soil classification in relation to clay minerals is the division of all soils into two broad groups, one having an acid reaction (low pH), the Pedalfers or non-Pedocals, the other with an alkaline reaction (high pH), the Pedocals. This distinguishes the two principal environments in which clay minerals in soils develop, although naturally there are innumerable minor variations.

An examination of the mineralogical composition of the clay fraction of soils by X-ray analysis has enabled M. L. Jackson *et*

¹ *Origin of Soils in Applied Sedimentation* (Wiley, New York), 1950, p. 41.

² I. Barshad, *op. cit.*, 1955.

al.¹ to postulate thirteen stages of weathering or weathering sequences, commonly found in the various kinds of soils. These are, in order of increasing intensity of weathering: gypsum, calcite, hornblende, biotite, albite, quartz, hydrous mica (illite), mica-intermediate, montmorillonite, kaolinite, gibbsite, hematite and anatase.

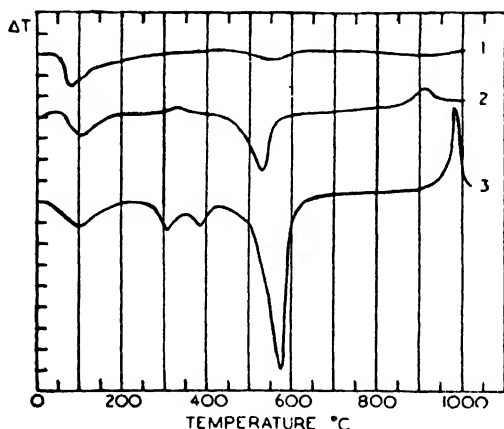


FIG. 60. The type of mineral in soil clays varies from north to south in the Northern Hemisphere as shown by differential thermal analyses.

1. Soil clay, Sweden—micaceous, and primary unaltered minerals.
2. Soil clay, Scotland—hydrous mica, Kaolin group mineral, vermiculite, montmorillonite.
3. Soil clay, West Africa—gibbsite, goethite, and metahalloysite.

Courtesy R. C. Mackenzie (1954, p. 132).

The weathering stage of a soil colloid is considered to be a resultant of intensity factors (temperature, moisture transfer, acidity and oxidation-reduction), and capacity factors (particle size, specific nature of the minerals), together with time. This concept together with that of C. C. Nikiforoff², which explains how a soil profile exists in a state of dynamic equilibrium, gives the framework within which the occurrence of clay minerals in soils can be described.

The clay minerals in soils should not be regarded as the stable end-products of weathering, but as part of a system existing in dynamic equilibrium with its components, as described by A. F. Frederickson³. Fig. 61 indicates the changes which can take place.

¹ *Op. cit.*, 1948.

² *Soil Sci.*, **67**, 1949, p. 219.

³ *Amer. Inst. Min. Met. Eng.*, 1952, p. 1.

The dominant clay minerals in some of the Great Soil Groups have been summarized by S. J. Toth¹ as follows:

TABLE 5
DOMINANT CLAY MINERAL TYPES IN SOIL GROUPS

Great Soil Group	Dominant Clay Mineral Type
Tundra	Hydrous mica (illite)
Desert	Mixed Layer
Red Desert	Hydrous mica (illite)
Chestnut	Montmorillonite
Chernozem	Hydrous mica or montmorillonite
Black earths, regur (India); margalitic soils, Indonesia; black turfsols, Africa; Australian black earths	
Prairie	Montmorillonite
Noncalic brown or Shantung	Montmorillonite
Podzols	Variable
Grey-brown podzolic	Hydrous mica (illite)
Red-yellow podzolic	Hydrous mica (illite) or kaolinite
Tropical and subtropical laterites	Kaolinite
Solonchak	Kaolinite (halloysite?)
Solonet	Similar to surrounding zonal type
Solodi	Similar to surrounding zonal type
Humic-gley and Weisenboden	Variable
Planosols	Montmorillonite
Rendzina	Variable
Alluvial	Montmorillonite and kaolinite
	Similar to surrounding zonal type

The first stage in soil-formation is the weathering of the rock-forming minerals, so that the question of mineral stability and chemical compositions has to be considered. Mineral stability depends very largely on the crystal-lattice structure, the most stable minerals having the simplest and most close-packed structure². I. Barshad³, giving an outline of the processes involved, stresses the importance of the weakest bond in the structure, for this determines where the break-down of the structure and alteration will start. This concept forms the basis of the reaction series described by M. L. Jackson *et al.*⁴

One of the most important mechanisms by which clay minerals develop from rock-forming minerals is ion-exchange, the principles

¹ Colloid Chemistry of Soils, *Chemistry of the Soil* (Reinhold, New York), 1955, p. 90. (Courtesy of Reinhold Publishing Company.)

² H. W. Fairbairn, *Geol. Soc. Amer., Bull.* 54, 1943, p. 1305.

³ *Chemistry of the Soil* (Reinhold, New York), 1955, p. 1.

⁴ *Op. cit.*, 1948.

of which were described earlier in this chapter (p. 295). The first stage in alteration is due to contact exchange between the ions in the moisture in a rock and those at the crystal-lattice boundaries¹. It is obvious that the finer the grain-size, the more of these boundaries will be available for the exchange to take place. Contact exchange is very similar to the exchange of ions which occurs between root-hairs and mineral grains². As soon as clay

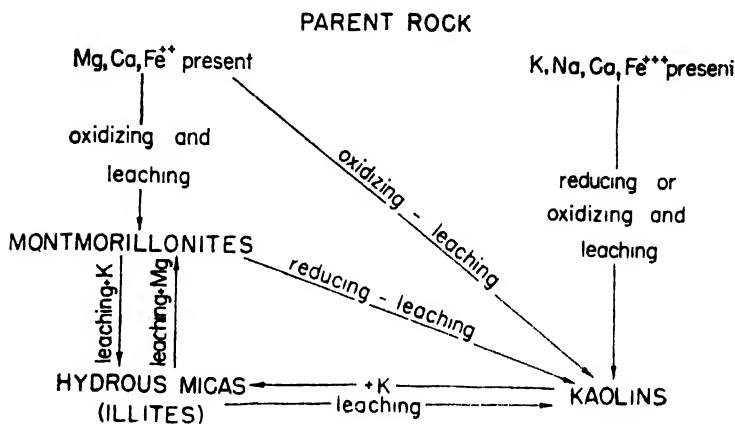


FIG. 61. Clay minerals formed under various weathering conditions. From A. F. Frederickson (1952, p. 6). Courtesy The American Institute of Mining and Metallurgical Engineers, New York.

minerals are formed they can act as weathering agents to induce further changes in such minerals as feldspars and amphiboles³.

The pH of the environment is important, for on it will depend whether certain cations will remain or be removed from the site of alteration; thus if magnesium and calcium remain, development of montmorillonite is possible; if potassium remains, micaceous minerals present will retain their stability. Other important reactions in mineral alteration are oxidation and reduction. All alteration processes depend on presence of water, which plays many roles in them.

Many excellent studies on the initial changes of rock-forming minerals to clay minerals have been made. The detailed investigations of J. B. Harrison⁴ showed the possibilities of examination of weathering rocks by chemical and microscopic procedures. He

¹ H. Jenny, *Journ. Phys. Chem.*, **40**, 1936, p. 501.

² H. Jenny and R. Overstreet, *Journ. Phys. Chem.*, **43**, 1939, p. 1185.

³ E. R. Graham, *Journ. Geol.*, **49**, 1941, p. 392.

⁴ The Katamorphism of Igneous Rocks under Humid Tropical Conditions, *Imp. Bur. Soil Sci.*, 1934.

drew attention to the importance of the resilication process in the development of kaolinite from initially formed gibbsite.

C. S. Ross and S. B. Hendricks¹ discussed a number of important points in development of clay minerals. Ferric iron enters the crystal lattice of the montmorillonite group minerals (nontronite is the ferruginous member), but cannot do this in the kaolinite structure, except in the case of chamosite (which requires special conditions for its formation), so that where kaolinite is the principal clay mineral in soils, free iron oxides also occur and are particularly abundant in the lateritic types of soils.

C. S. Ross and S. B. Hendricks found that soils derived from Triassic diabase (in the Piedmont region of the eastern United States) are generally composed essentially of montmorillonite, whereas some of the other ferromagnesian-bearing rocks of the region, under similar physical and climatic conditions, have weathered to kaolinitic soils. In diabase, the ferromagnesian minerals and feldspar break down together, releasing iron (part of it ferrous), magnesium, aluminium and silicon, giving conditions favourable to formation of montmorillonite. In other rocks, the magnesium from ferromagnesian minerals is removed by solution and the iron is either eliminated or oxidized. In the absence of magnesium and with iron absent or effectively isolated from reaction by oxidation, kaolinite forms.

Detailed examination of rock weathering and soil formation in the same general Piedmont area by J. G. Cady² confirmed the importance of the early mineralogical changes described by C. S. Ross and S. B. Hendricks³. The first weathering products in the diorite, which give rise to the Davidson soil, are gibbsite, chlorite and allophane; later stages of weathering contain only kaolinite, quartz and iron oxides. The feldspar in the parent rock of the Iredell (or Mechlenburg) loam, a meta-gabbro, alters to halloysite, which remains the principal clay mineral throughout the profile, but is accompanied by goethite, kaolinite and chlorite.

Gibbsite as the first alteration product in rock weathering has also been described by L. T. Alexander *et al.*⁴ The gibbsite is later silicified to form kaolinite, the necessary silica being released by the continued alteration of the rock minerals.

The variations in clay minerals which occur in a profile of Montalto silt loam, developed on meta-gabbro in the Piedmont region in Maryland, were found to be as follows: kaolinite is the predominant clay mineral throughout the profile; in the C horizon

¹ *Op. cit.*, 1945.

² *Soil Sci.*, **50**, 1951, p. 337.

³ *Op. cit.*, *Soc. Amer. Proc.*, 1945.

⁴ *Soil Sci.*, **6**, 1942, p. 52.

it makes up 45–60% of the colloid fraction, but it decreases to about 15% at the surface. It is accompanied throughout by a little gibbsite. Other clay minerals, in the A and B horizons, are a micaceous clay mineral and chlorite and/or vermiculite. Mineralogical data for the sand fractions indicate that the profile probably developed in two stages, lateritic at the base and podzolic in the A and B horizons¹.

In monogenetic soils developing from parent material which contains mica, the weathering sequence of the mica, under podzolic conditions, can be determined by the variation of the d spacing (001) measured by X-ray diffraction². As weathering progresses the K⁺ ion binding the mica sheets together is removed and replaced by other ions, which increase the hydration of the mineral and consequently the d spacing from 10Å to nearly 14Å. This relationship is easily seen in patterns obtained with a wide-range goniometer X-ray diffractometer; in this technique the mineralogy of each clay fraction can be shown on the chart in its correct position in the soil profile³.

A soil developed on limestone under podzolic conditions was found to show considerable variation in the clay minerals in different horizons⁴. The parent-rock is an impure limestone containing hydrous mica and a little montmorillonite. As the top of the profile is reached, kaolinite and chlorite and/or vermiculite, increase as hydrous mica decreases (Fig. 62). This illustrates the use of the recording X-ray diffractometer in interpreting soil clay-mineral changes in different horizons in a soil profile.

The clay minerals have been identified in soils from many parts of the world, so that the following examples should be regarded as a selection of available information. In some investigations only the clay minerals in the surface soil have been identified, whereas in others, mineralogical changes in the whole soil profile have been described. The soil clay-minerals have largely been related to members of the Great Soil Groups, but some of the earlier work was only related to the kind of parent material. Some studies should be regarded as reconnaissance, in that they give information about a few selected samples from large areas.

Clay minerals in the south-eastern part of the United States have received considerable attention. In Florida soils, for example,

¹ D. Carroll, *Soil Sci.*, **75**, 1953, p. 87.

² B. N. Rolfe and C. D. Jeffries, *Science*, **116**, 1952, p. 599; *Clay Min. Bull.* **2**, 1953, p. 85.

³ C. D. Jeffries, *Soil Sci.*, **14**, 1949, p. 378.

⁴ D. Carroll and J. C. Hathaway, Clay Minerals in a Limestone Soil Profile, Clays and Clay Minerals, *Proc. 2nd Nat. Conf. Clays and Clay Min.*, *Nat. Acad. Sci. Nat. Res. Council Pub.* **327**, 1954, p. 171.

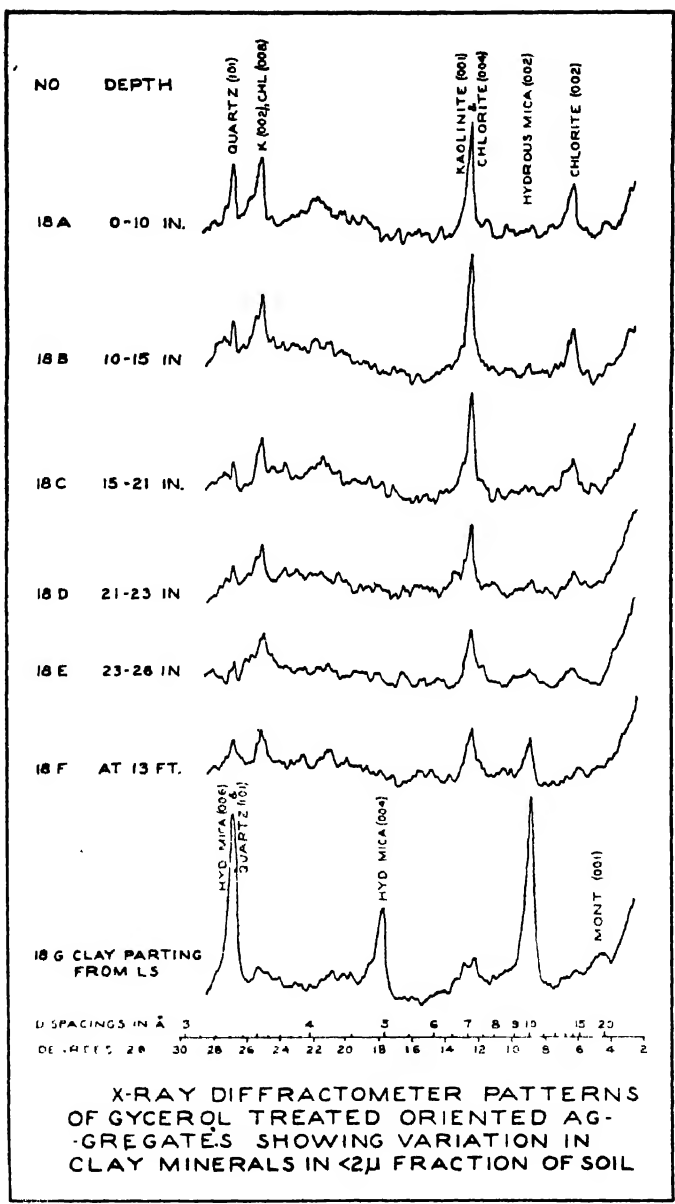


FIG. 62

J. G. A. Fiskel and S. B. McCaleb¹ have described kaolinite, illite, montmorillonite, vermiculite, hydrous mica, gibbsite, feldspar and quartz, found in various proportions in the clay fraction.

The mineralogical changes taking place in soil formation from acid and basic igneous rocks in the north central part of the United States, have been described in considerable detail by R. P. Humbert and C. E. Marshall². The clay minerals formed are members of the montmorillonite group together with some mica-ceous minerals. The pH of these soil profiles is not high.

Soils developed over loess overlying glacial drift have been described by E. P. Whiteside and C. E. Marshall³, who found that the clay fractions were mixtures of the kaolinite, illite and montmorillonite groups. There was a pronounced horizon differentiation which resulted in different quantities of clay fraction throughout the profile. The importance of examining different grades within the clay fraction is emphasized because of variation in the amounts of the different clay minerals with size.

In tropical soils two principal environmental types are readily recognizable, the lateritic with dominant kaolinite, and the regur and other black earths with dominant montmorillonite. The lateritic soils develop under acid conditions with thorough leaching, but the black soils develop under seasonal rainfall without leaching and in an alkaline environment. These black earths include the regur of India⁴, the margilic soils of Indonesia⁵, the African black soils⁶ and the Australian black earths⁷.

In a recent study of clay minerals in black earths and red loams developed from basalt in an area in Queensland, J. A. Ferguson⁸ found that a member of the montmorillonite group forms in early stages of weathering under restricted leaching and oxidation (black earths), but that in older soils in more humid situations, kaolinite develops (red loams). An important factor is the removal of iron from the montmorillonite lattice to the outside of the kaolinite micelles as an oxide. This results in greater porosity and reduction in exchange capacity of the soil⁹.

Australian soils which develop gilgais (hummocks and hollows) were found to contain montmorillonite as the principal clay

¹ *Soil Sci.*, **76**, 1953, p. 431.

² *Univ. Missouri Coll. Agric. Res. Bull.* **359**, 1943.

³ *Univ. Missouri Coll. Agric. Res. Bull.* **386**, 1944.

⁴ R. W. Simonson, *Journ. Soil Sci.*, **5**, 1954, p. 275.

⁵ E. C. J. Mohr and F. A. van Baren, *Tropical Soils. A Critical Study of Soil Genesis as Related to Climate, Rock and Vegetation (Interscience, New York)*, 1954.

⁶ C. R. van de Merwe, *Bur. Soil Sci. Tech. Commun.* **46**, 1949, p. 128.

⁷ J. S. Hosking, *Journ. Counc. Sci. Ind. Res. (Austr.)*, **21**, 1948, p. 21.

⁸ *Austr. Journ. Agric. Res.*, **5**, 1954, p. 98.

⁹ J. J. Fripiat and M. C. Gastuche, *op. cit.*, 1952.

mineral, by E. G. Hallsworth *et al.*¹ The amount of sodium in the exchange complex is an important factor in the swelling capacity of these soils. Examination of the clay minerals in black and chocolate soils² revealed that illite is present with kaolinite and montmorillonite in the chocolate soils, whereas the black soils contain only montmorillonite. Black soils in Andalusia (Spain), developed on calcareous sandstone, contain montmorillonite with a little illite³.

Soils from dry regions around the Mediterranean show a variety of clay minerals which are largely due to the influence of the parent material. Of interest is attapulgite in the calcareous yellowish brown loam derived from chalky marls in desert areas in Syria and Lebanon; it is associated with a kaolin mineral and mica-ceous material⁴. The influence of the parent material is important, as noted by A. Reifenberg⁵, who found that the soil derived from holocrystalline basalt contained kaolin mineral with vermiculite and goethite, whereas a basalt with a glassy ground-mass produces montmorillonite in the soil derived from it.

In Dutch soils, H. W. van der Marel⁶ reported the following occurrences of clay minerals (parent material or origin in parentheses): mainly illite (sea-clays); illite with some montmorillonite (river clays—the Rhine carries some montmorillonite); montmorillonite with kaolinite (residual from soft limestones); illite and a little montmorillonite (boulder clays); illite with a little kaolinite, boehmite and montmorillonite (loess); kaolinite plus illite (tertiary or older sediments).

W. A. Mitchell⁷ found in south-east Scotland that illite is the clay mineral derived from the more acidic types of rocks such as granite, whereas basalt, norite and diabase give rise to soils in which montmorillonite and vermiculite are in excess of illite.

In Germany detailed examination of soil profiles developed on basalt, limestone and sandstone by H. Huffmann⁸ showed that halloysite occurred in the basaltic soil and in the weathered basalt; illite in the limestone soil, and kaolinite in the sandstone soil. The clay mineralogy was determined in six profiles on terraces of the Middelriss, Hauptwurm and Altriss by M. Salger⁹. Illite and kaolinite were present in all samples, but the amount of kaolinite had doubled in the soils compared with the original loess.

¹ *Journ. Soil. Sci.*, **6**, 1955, p. 1. ² *Journ. Soil Sci.*, **3**, 1952, p. 103.

³ M. Taboada, *Journ. Soil Sci.*, **4**, 1953, p. 48.

⁴ A. Muir, *Journ. Soil Sci.*, **2**, 1951, p. 163.

⁵ *Journ. Soil Sci.*, **3**, 1952, p. 68.

⁶ *Trans. 4th Inter. Cong. Soil Sci.*, **2**, 1950, p. 92.

⁷ *Op. cit.*, 1955.

⁸ *Heidel. Beiträge Min. Petrog.*, **4**, 1954, p. 67.

⁹ *Heidel. Beiträge Min. Petrog.*, **4**, 1954, p. 288.

The clay minerals developed in a soil formed on Cretaceous greensand under podzolizing conditions were described by W. F. Cole¹. It was found that the glauconite in the subsoil had largely changed to montmorillonite and a little kaolinite and that in the the surface soil or A horizon, the original glauconite of the greensand had been replaced by a mixture of kaolinite, goethite and quartz. Other types of Australian soils described by A. Karim² contained largely illite in the clay fraction. He observed that kaolinite appeared to be replacing illite in soils which showed a distinct podzolic nature. J. S. Hosking³ has summarized the occurrence of the clay minerals in various types of Australian soils.

Allophane has been found to be the principal clay mineral in soils formed from volcanic ash showers in New Zealand⁴. Both andesitic and rhyolitic ash gave rise to this mineral, providing a contrast to the montmorillonite which similarly arises from volcanic ash in the United States. In Japan, T. Sudo⁵ found that several stages in the alteration of volcanic ash to soil-clays could be recognized. He gives these as follows (from the surface downwards): unaltered volcanic glass, allophane, hydrated halloysite; or, montmorillonite (acid clay), montmorillonite (bentonite). He states: '... weak alkaline conditions coupled with poor leaching, e.g. conditions obtained below the water table, may produce an environment favourable to the formation of montmorillonite. On the other hand, weak acidic or neutral conditions coupled with good leaching, such as occur in surface-water circulation, favour the formation of kaolinitic clays or montmorillonite (acidic). Geological time may be necessary for the course of crystallization from volcanic glass through allophane to hydrated halloysite.'

In investigations of soil-clay minerals it has frequently been found that certain types are produced from definite parent minerals.

For example, G. F. Walker⁶ found that biotite gives rise to a trioctahedral micaceous mineral in soils in north-eastern Scotland. G. Brown⁷ has reported a clay mineral in soils from the north-west of England, which appears to be the dioctahedral analogue of vermiculite and derived from a dioctahedral mica. After investigation of the weathering of four different types of crystalline rocks, I. Stephen⁸ concludes that soils from ultrabasic rocks contain clay minerals of chlorite-vermiculite type, while those from the granite

¹ *Journ. Roy. Soc. W. Austr.*, 27, 1941, p. 229.

² *Journ. Soil Sci.*, 5, 1954, p. 140.

³ *Op. cit.*, 1948.

⁴ K. S. Birrell and M. Fieldes, *Journ. Soil Sci.*, 3, 1952, p. 156.

⁵ *Clay Min. Bull.*, 2, 1954, p. 96.

⁶ *Miner. Mag.*, 28, 1949, p. 693.

⁷ *Clay Min. Bull.* 2, 1953, p. 64.

⁸ *Journ. Soil Sci.*, 3, 1952, pp. 20 and 219.

contain mainly illite. This is illustrated in Fig. 63. Under acid leaching conditions, feldspar \rightarrow illite \rightarrow kaolin; under alkaline conditions he postulates alteration of illite to montmorillonite product.

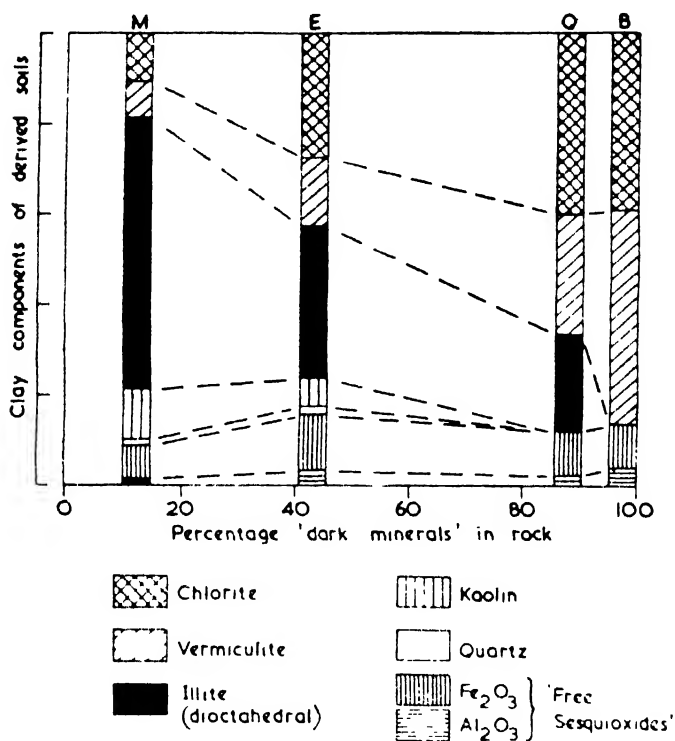


FIG. 63. Variation in the constitution of the clays of the derived soils with difference in parent bed-rock.

M = granite; E = 'Ivy-Scar rock' (granophytic quartz micro-diorite); Q = appinite; B = biotite.

Courtesy I. Stephen (1952, p. 234).

Interlayered or interstratified clay minerals are of common occurrence in soil-clays and in deposits such as the Keuper Marl. D. B. Honeyborne¹ has described a mineral from the British Keuper Marl, the X-ray diffraction data of which indicate that it is made up of alternate layers of hydrated chloritic and montmorillonitic types. This appears to be similar to the 'corrensite' described by F. Lippman² from the Keuper Marl in Germany. I. Stephen and D. M. C. MacEwan³ have described a 'swelling chlorite' which

¹ *Clay Min. Bull.*, 1, 1951, p. 150.

² *Heidel. Beiträge Min. Petrog.*, 4, 1954, p. 130.

³ *Op. cit.*, 1951.

apparently originated as an alteration product of hornblende, in a soil derived from a basic rock. 'Cardenite', a trioctahedral montmorillonite, derived from alteration of ferromagnesian minerals of basic types of rock under conditions of poor drainage, has been described by D. M. C. MacEwan¹. It is thought that trioctahedral mica is the first stage in the alteration to trioctahedral montmorillonite. 'Rectorite', which has a structure indicating interstratified pyrophyllite-like and vermiculite-like layers, has been described by W. F. Bradley².

M. L. Jackson *et al.*³ have reported results of detailed investigations of a number of clay fractions of soils of different types from various localities in the United States and Hawaii. They found that most clays are polycomponent, with a general occurrence of interstratification of the clay minerals. This interstratification may possibly involve a 'superlattice' which reflects the stage of the weathering sequence previously described⁴. It is probable that mixed-layering will occur during evolution of the soil-clay minerals to those which are in equilibrium with the micro physico-chemical environment in which they are situated.

THE MARINE ENVIRONMENT

The marine environment is generally divided into two principal types, the littoral (near-shore) and the deep sea or ocean floor environments. The littoral is probably the more complex, because of variation in topography due to irregularities of the edges of land-masses and in type and quantity of clay minerals deposited from the erosion of these land-masses by rivers.

It is somewhat obvious to mention that the clay minerals are deposited in sea-water with a more or less uniform and stable chemical composition, but any changes that take place in these minerals must be considered as results of chemical reactions which will vary slightly from place to place; for example, the influx of much fresh water, as in estuaries, from rivers in flood, lowers the salinity and the amount of sodium, potassium, magnesium, calcium, etc., which is available to react with the clay minerals. The reactions between clay minerals and sea-water are similar to those with other electrolytes. The divalent ions enter the exchange reactions in the minerals in preference to the univalent cations⁵.

¹ *Clay Min. Bull.*, 2, 1954, p. 120.

² *Amer. Min.*, 35, 1950, p. 590.

³ Some Analyses of Soil Montmorin, Vermiculite, Mica, Chlorite and Interstratified Layer Silicates, *Clays and Clay Minerals, Proc. 2nd Nat. Conf. Clays and Clay Minerals, Pub. 327, Nat. Acad. Sci. Nat. Res. Bull.*, 1954, p. 218.

⁴ M. L. Jackson *et al.*, *op. cit.*, 1948.

⁵ D. Carroll and H. C. Starkey, *Proc. 7th Nat. Clay Conf.* (Pergamon Press, London), 1960.

The structure and chemical composition of the individual clay minerals will themselves decide what the end-products will be in any environment.

The marine environment is basic, with a pH of about 7-9; thus cations will not be removed, but may be added. Theoretically, the principal clay minerals adjusted to this environment will be hydrous micas (illites), chlorites and montmorillonites¹ and, in fact, a number of investigators have found that illite is the commonest and kaolinite the least abundant of the clay minerals in this environment as, for example, in the Gulf of California².

Clay mineral studies in the vicinity of Rockport, Texas, on the northern Gulf of Mexico, by R. E. Grim and W. D. Johns³, provide interesting data on the diagenesis of these minerals in a number of near-shore environments, including bays, lagoons and deltas, as well as the open Gulf of Mexico. The Guadalupe River, which discharges into San Antonio Bay, closed by barrier islands, carries montmorillonite with a little chlorite and illite, with only a trace of kaolinite. Clay minerals in the watershed of the Guadalupe River, examined by L. H. Simmons and M. S. Taggart⁴ are predominantly montmorillonite, kaolinite and illite, but vary with the presence of different geological formations. R. E. Grim and W. D. Johns⁵ divided the depositional area into a number of units and it was found that there was a systematic decrease in montmorillonite and an increase in illite and chlorite from the river to the open Gulf environment. This is shown in Fig. 64. It was found that the open Gulf sediments contain glauconite in the coarser fractions. In diagenesis it is considered that illite and chlorite develop from montmorillonite by cation exchange mechanisms, in which the presence of organic matter may have an important retarding effect in sediments deposited nearest the river mouth. Although the alteration of montmorillonite to illite and degraded illite to illite and chlorite has as yet received no satisfactory explanation, the fact remains that regeneration does occur under marine conditions and montmorillonite disappears.

The complexity of the change of montmorillonite has been discussed by M. D. Foster⁶ as follows: 'Conversion of "illite" to

¹ G. Millot, *Geol. Appliq. Prosp. Min.*, **2**, 1949, p. 11.

² R. E. Grim, R. S. Dietz and W. F. Bradley, *Bull. Geol. Soc. Amer.*, **60**, 1949, p. 1785.

³ Clay Mineral Investigation in the Northern Gulf of Mexico, *Clays and Clay Minerals, Proc. 2nd Nat. Conf. Clays and Clay Minerals*, 1954, p. 81.

⁴ Clay Mineral Content of Gulf Coast Outcrop Samples, *Clays and Clay Minerals, Proc. 2nd Nat. Conf. Clays and Clay Minerals*, 1954, p. 104.

⁵ *Op. cit.*, 1954.

⁶ The Relation between Illite, Beidellite and Montmorillonite, *Proc. 2nd Nat. Conf. Clays and Clay Minerals*, 1954, p. 386.

montmorillonite or vice versa would require a much more deep-seated alteration than simple removal of potassium from "illite" and its replacement of sodium, calcium or magnesium, or the fixation of potassium between the layers of a montmorillonite.'

An investigation of clay mineral diagenesis in the Chesapeake Bay area (eastern United States) by M. C. Powers¹ substantiates

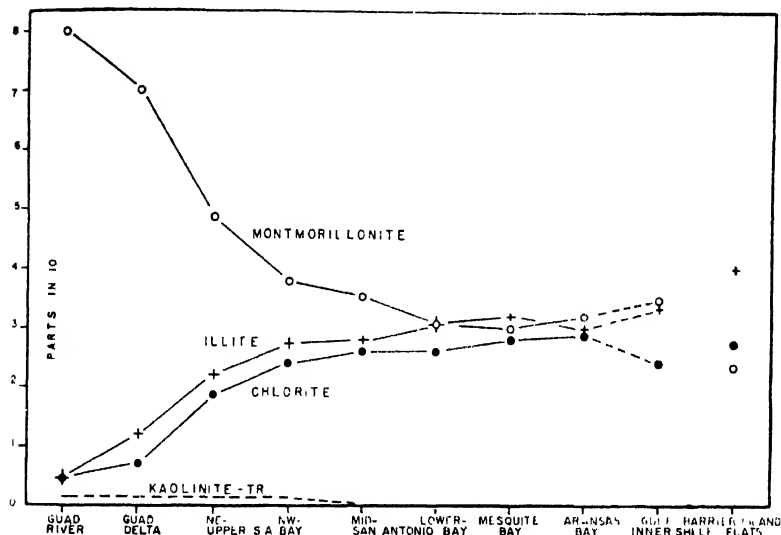


FIG. 64. Relation of clay mineral composition to geographical location in the Rockport area, northern Gulf of Mexico.

Courtesy R. E. Grim and W. D. Johns (1954, p. 95).

the results obtained by R. E. Grim and W. D. Johns² that chlorite is forming in near-shore marine environments. Rivers draining into Chesapeake Bay carry illite, degraded illite together with a little kaolinite and degraded chlorite. Newly formed chlorite apparently arises from degraded illite by the addition of brucite layers to the illite basal surfaces. This brucite structure is supposed to grow across the illite surface with increasing time and salinity, tying the silicate layers together and thus increasing thermal stability of the chlorite produced. The amount of chlorite formed and its thermal stability are a function, in part, of the concentration of magnesium in solution and the ratio of illite to degraded illite reaching the estuarine environment.

¹ Clay Diagenesis in the Chesapeake Bay Area. *Clays and Clay Minerals, Proc. 2nd Nat. Conf. Clays and Clay Minerals*, 1954, p. 68.

² *Op. cit.*, 1954.

The investigations of J. C. L. Favajee¹ on muds in the Wadden Sea in the Netherlands provide interesting information. He found that there was a difference in mechanical composition between the marine mud and that brought down by the rivers and deposited in the bay (the rivers are the Eems, Wezer, Elbe and Rhine). In the marine mud there is a definite constant ratio between the quantities of the fractions below 25 microns. The river muds have no discernible ratios in these fractions. X-ray examinations were made of the 0-0.5, 0.5-2 and 2-10 micron grades. The marine muds contained, in the finest fraction, 80-90% illite, 5-10% kaolinite and 3.5-10% montmorillonite. The river muds differed in that the montmorillonite was 0-3% and illite 70-90%; there was little change in the quantity of kaolinite. These figures are averages of a considerable number of analyses. It was concluded that the Wadden mud is marine (by marine is meant an origin from the North Sea). Mineralogical analyses of the sand fractions by R. D. Crommelin² substantiated the results of the clay mineralogy.

In the marine environment some clay minerals have been formed under special conditions; two important clay minerals in this class are glauconite and chamosite. Glauconite, as is well known, is a major constituent of greensands and has been the subject of many investigations. S. B. Hendricks and C. S. Ross³ have summarized the information and have shown that glauconite is a dioctahedral mica allied to the hydrous micas, from which it differs in containing less magnesium and also in the interlayer cations (see p. 319). Structural requirements for glauconite for the presence of certain cations are important; thus the average interlayer ionic ratios (in equivalents) are approximately Na:Ca:K::0.15:0.20:1.0. Sea-water contains these elements in the ratios of 46.3:2.10:1.0; therefore the ratios necessary to the glauconite structure are obtained by competition of the ions for the available sites; this depends on the affinity of these ions for the sites.

Investigations of marine sediments have indicated that hydrous mica (illite) is the principal clay mineral present in most areas, so that under reducing conditions, whereby Fe^{+3} is changed to Fe^{+2} , glauconite will develop.

The physical condition of the marine mud may be important, as mentioned by P. G. H. Boswell⁴. There probably will be a difference in the reactions which can take place in soft settlement, characterized by the flocculent state which may be thixotropic,

¹ The Origin of the 'Wadden' Mud, *Meded. Landbouwh. Wageningen*, **5**, 1951, p. 113.

² *Verh. Geol. Mijn. Gen. Geol.*, Serie 13, 1943, p. 299.

³ *Op. cit.*, 1941.

⁴ *Clay Min. Bull.*, **1**, 1952, p. 246.

and marine sedimentation is liable to have soft settlement of deposits. The often uniform grain size of glauconite may be an indication of the physical conditions of deposition. Hard packing could conceivably result in retention of hydrous micas.

Chamosite is another mineral (p. 315) which apparently is characteristic of shallow marine environments; it may be as indicative of its environment as is glauconite, but at present it is not so well understood. Chamosite is a ferrous kaolinite and is an important iron-bearing mineral of certain sedimentary iron-ores, such as the Clinton ores of the United States, the Northampton Ironstone formation (England), the oolitic iron ores of Germany and several others whose occurrence has been discussed by J. H. Taylor¹.

As glauconite is analogous to hydrous mica (illite), so chamosite (or a large part of it) is analogous to kaolinite (the chloritic type of chamosite is not considered in this context). It has been noted that hydrous mica (illite) is a very common constituent of marine muds; but if the land surface being eroded was only able to supply kaolinite in large quantities as, for instance, in tropical regions with lateritic soils, then that would be the clay mineral deposited in the marine environment.

Kaolinite may become soluble to a certain extent in sea-water, but only very limited cation exchange can take place, because of its structure, and the K^+ ion cannot enter the crystal lattice. Another point of interest is that in most environments kaolinite cannot take iron, either ferrous or ferric, into its structure, and in tropical soils subject to strong acid leaching (and in podzols), the iron exists as a film on the kaolinite plates, as described by J. J. Fripiat and M. C. Gastuche².

The ferric iron will be transported along with the kaolinite; under reducing conditions, in the presence of sulphides, the iron oxide film will be removed and the ferrous iron may react with the kaolinite. It is not inconceivable that strong floods by rivers entering a shallow restricted part of the sea will deposit both iron-coated kaolinite and organic debris to produce the requirements for genesis of chamosite. The fact that the deposition of the Northampton Ironstones was terminated by a change to estuarine and deltaic conditions³ may be geological evidence for this suggested mode of origin of chamosite.

The clay minerals in deep-sea sediments have only received limited X-ray examination. In the South Atlantic, C. W. Correns⁴

¹ Petrology of the Northampton Sand Ironstone Formation, *Mem. Geol. Surv. Gt. Brit.*, 1949.

² *Op. cit.*, 1952. ³ J. H. Taylor, *op. cit.*, 1949, p. 88.

⁴ Die Sedimente des Äquatorialen Atlantischen Ozeans, Deutsche Atlantischen Exped. Meteor 1925-27, *Wiss. Ergeb.*, 3, 1937, p. 3.

found that illite was the predominating clay mineral, but that kaolinite and montmorillonite also occurred. Halloysite, owing to the difficulty of its identification, was doubtfully recorded, although its distribution is given on a map by that author¹.

Cores obtained by the *Swedish Albatros* expedition collected at about 1,000 km. from the Brazilian coast, were examined by F. W. Locher² and compared with two from the *Meteor* expedition collected from near the mouth of the Amazon. It was found that the red clay is a mixture in various proportions of illite and kaolinite and that chlorite occurred in blue clay. The kaolinite content was higher in the *Meteor* samples. Halloysite may occur in very small quantities in the blue clay. The *Snellius* expedition³ obtained a few clay mineral determinations from sediments in the East Indian Archipelago; here, too, illite, kaolinite and montmorillonite were found.

CLAYS OF HYDROTHERMAL ORIGIN

The solutions accompanying mineralization are responsible for alteration of minerals of the country rock into clay minerals. The ferromagnesian minerals will produce chlorite and montmorillonite, but if the hydrothermal conditions are sufficiently prolonged and intense, kaolinite will be formed. R. E. Grim⁴ has summarized available information. He finds that there is a general tendency for sericite to be nearest the mineral vein; next, an intermediate zone of kaolinite, halloysite, allophane and/or montmorillonite; followed by an outer zone of chlorite. C. S. Ross and P. F. Kerr⁵ have shown that dickite is very often formed by vein-alteration. That hydrothermal alteration can take place on a large scale is shown by the china clays of Cornwall.

CLAY MINERALS IN LOESS

X-ray examination of the <2 micron fraction of loess from European and United States localities⁶, from Limburg, Holland⁷, from China⁸, and from the Tropics⁹, has shown that there is consider-

¹ *Ibid.*

² *Heidel. Beiträge. Miner. Petrog.*, **3**, 1952, p. 193.

³ P. H. Kuenen, The *Snellius Expedition in the Eastern Part of the Netherlands East Indies (Brill. Leiden)*, **5**, 1943.

⁴ *Op. cit.*, 1953, p. 328.

⁵ *U.S. Geol. Surv. Prof. Paper* **165E**, 1931.

⁶ A. Swineford and J. C. Frye, *Journ. Geol.*, **59**, 1951, p. 306; *Journ. Sed. Pct.*, 1955, p. 3.

⁷ H. W. van der Marel, *op. cit.*, 1950.

⁸ Y. Hseung and M. L. Jackson, *Soil. Sci.*, **16**, 1952, p. 294.

⁹ R. Coleman and M. L. Jackson, *Soil Sci.*, **10**, 1945, p. 381.

able variation in the clay minerals present both as regards kind and amount. The following is a summary of their findings.

Kansas Loess. Montmorillonite, with minor quantities of illite and kaolinite; common to the loess throughout Kansas, Nebraska, South Dakota and southwestern Iowa.

Torino, Italy. Dominantly muscovite, ? mixed-layer chlorite-montmorillonite.

St. Vallier, France. Mainly illite (or illite and muscovite) and an expanding montmorillonite group mineral.

Strasbourg-Achenheim, France. Two samples from this locality differed, one contains a 14.7Å mineral and kaolinite with illite and the other is illite, the 14.7Å mineral and a little kaolinite.

Heidelberg, Germany. 14.7Å mineral, illite and kaolinite.

Eltville-Wiesbaden, Germany. Illite, 14.7Å mineral, little kaolinite.

Landen-Liege, Belgium. Montmorillonite, illite and kaolinite.

Limburg, Holland. Illite, kaolinite, boehmite and montmorillonite.

China. Loess in China as a soil-parent material has been examined by Y. Hseung and M. L. Jackson¹ who found that these soils in China contain much smaller amounts of montmorillonite than those of similar origin in the United States. This may be due to the warm dry climate in the inter-glacial period in the loess regions of China. Soils developed in the drier areas from loess have a higher illite content than the others; kaolinite is not developed in the coldest climate; soils formed under higher rainfall contain more vermiculite and montmorillonite.

United States. A soil developed from a loess in a warm humid climate contained moderate amounts of montmorillonite with a poorly defined basal spacing².

CLAY MINERALS IN SEDIMENTARY ROCKS

The most interesting and informative discussion of the occurrence of clay minerals in sedimentary rocks is that of G. Millot³ who made a statistical examination of the clay minerals in Mesozoic and Tertiary rocks of known environment in eastern France. These rocks represented lacustrine or fluvio-lacustrine, lagoonal continental facies and marine environments. He concludes that there are two principal types of environmental conditions: (1) acid-leaching, with removal of cations; and (2) basic, rather stagnant, waters which cause the accumulation of cations. (These are similar to the base unsaturated and base saturated soil conditions which give rise to definite clay minerals in soils.) In (1) kaolinite predominates, the pH of the rock is acid and refractory clays are produced; in (2) the dominant clay minerals will be illite, chlorite,

¹ *Op. cit.*, 1952.

² R. Coleman and M. L. Jackson, *op. cit.*, 1945.

³ *Op. cit.*, 1949.

montmorillonite, alternatively, members of the palygorskite group. Informative discussions are given in papers by J. H. Taylor¹ and by P. G. H. Boswell².

Many sedimentary rocks contain clay minerals as essential constituents, e.g. shales and mudstones. Hydrous micas and chlorites are the most plentiful of the clay minerals here, but the type of mineral depends to a certain extent on the environment in which the sediment was deposited, e.g. glauconite in greensands, chamosite in certain iron-ores, montmorillonite in bentonites.

In the older sedimentary rocks hydrous micas predominate where their presence may in part be caused by consolidation and pressure. Palaeozoic limestones from Illinois studied by R. E. Grim *et al.*³ contained dominantly hydrous mica, with a little kaolinite present in some specimens. F. B. van Houten⁴ identified the clay minerals in a number of sedimentary rocks and found that hydrous mica predominates. C. Robins and W. D. Keller⁵ found that hydrous mica was the principal clay mineral in a series of limestones and dolomites of marine and fresh-water origin, ranging in age from Palaeozoic to Recent, but kaolinite and montmorillonite were also found. W. D. Keller⁶ found that the green colour in most common sedimentary rocks is caused by hydrous mica, sometimes by montmorillonite.

H. H. Murray⁷ has discussed the genesis of clay minerals in some Pennsylvanian shales of Indiana and Illinois. He found that in non-marine shales kaolinite, chlorite and illite were present in about equal proportions, whereas the change to brackish and marine conditions caused an increase in illite at the expense of kaolinite and chlorite.

It was noted in descriptions of individual minerals that acid has an appreciable effect on some clay minerals, and that some, e.g. chlorite, are dissolved by hydrochloric acid. The usual method of preparing insoluble residues from limestones has been to dissolve the rock in this acid, which may alter the clay minerals appreciably, so that it would appear to be preferable to use dilute acetic acid (1:4) for this purpose, or even to obtain the insoluble residue by means of an ion-exchange resin in the hydrogen form.

¹ *Op. cit.*, 1952.

² *Op. cit.*, 1952.

³ *Amer. Min.*, **22**, 1937, p. 813.

⁴ *Amer. Journ. Sci.*, **251**, 1953, p. 61.

⁵ *Journ. Sed. Pet.*, **22**, 1952, p. 146.

⁶ *Journ. Sed. Pet.*, **23**, 1953, p. 3.

⁷ Genesis of Clay Minerals in some Pennsylvanian Shales of Indiana and Illinois, *Clays and Clay Minerals, Proc. 2nd Nat. Conf. on Clays and Clay Minerals*, 1954, p. 47.

VARIOUS TYPES OF RESIDUAL AND TRANSPORTED CLAYS
Under conditions of long-continued or intense weathering, considerable thicknesses of residual clays may be formed. Thus, removal of calcium carbonate from limestone will result in accumulation of the clay minerals present as impurities in the limestone, Clay-with-Flints being a well-known example of residuum from chalk.

Special types of residual clay will form under specific conditions; flint clays, fireclays and diaspore clays, described by W. D. Keller *et al.*¹ from Missouri, are examples. These clays, deposited in sink-holes in a weathered limestone land-surface, consist of disordered kaolinite, illite and diaspore in various proportions. Swampy conditions with water having an acid reaction, and leaching of originally deposited clay materials, are considered responsible for their origin, although the genesis of diaspore instead of gibbsite is not completely understood. Boehmite, however, has been found.

Other fireclays originate as seat-earths below coal-seams and similar reducing conditions with a low pH and negative eH are considered essential for their formation. Present-day conditions in tropical forests of Sumatra, Indonesia and Borneo, with accumulation of organic matter in a waterlogged state and development of kaolinite in the underlying soil, are described by E. C. J. Mohr and F. A. van Baren² and by B. Polak³.

Laterites and bauxites are other types of residual material in which clay minerals, particularly kaolinite, are important constituents. Laterites are the result of leaching in warm, moist climates under oxidizing conditions. By desilication of kaolinite, gibbsite is formed, but boehmite and diaspore also occur in bauxites. The stratigraphy and origin of bauxite deposits have been reviewed by E. C. Harder⁴ and details of the petrography in some bauxite and diaspore deposits are given by V. T. Allen⁵. A bibliography of laterite and bauxite literature has recently been prepared by E. C. Fischer⁶.

In the following pages brief notes concerning some different types of clay deposits are given. Such deposits are often due to the environmental conditions of deposition⁷.

¹ Origin of the Missouri Fire Clays, *Clays and Clay Minerals, Proc. 2nd Nat. Conf. Clays and Clay Minerals*, 1954, p. 7.

² *Op. cit.*, 1954, p. 317.

³ Occurrence and Fertility of Tropical Peat Soils in Indonesia, *Trans. 4th Intern. Cong. Soil Sci.*, 2, 1950, p. 183.

⁴ *Geol. Soc. Amer. Bull.*, 60, 1949, p. 887.

⁵ *Geol. Soc. Amer. Bull.*, 63, 1952, p. 649.

⁶ *U.S. Geol. Surv. Bull.*, 999, 1955.

⁷ G. Millot, Prospecting for Useful Clays in Relation to their Conditions of Genesis. Symposium. Problems of Clay and Laterite Genesis, *Amer. Inst. Min. Engin.*, 1952, p. 107.

Bentonite. According to C. S. Ross and E. V. Shannon¹ 'Bentonite is a rock composed essentially of a crystalline clay-like mineral formed by devitrification and accompanying chemical alteration of a glassy igneous material, usually a tuff or volcanic ash'. The clay mineral is montmorillonite. The name was originally given to the type of clay occurring in the Fort Benton shale (Cretaceous) at Rock Creek, Wyoming².

D. F. Hewitt³ recognized that bentonites contain minerals characteristic of volcanic rocks. C. S. Ross and E. V. Shannon⁴ and C. S. Ross and S. B. Hendricks⁵ have described bentonites and their constituent minerals in detail.

Bentonites are among the purest of all clay materials and, although originally recognized in the western United States, they have now been found in many parts of the world. In thin section bentonites have a texture characteristic of the volcanic ash from which they have altered. Three principal textural types were described by C. S. Ross and S. B. Hendricks⁶: very fine-grained pumice; a type in which gas bubbles were larger and had the shape of flattened lenses; and a third type which contained more or less spherical bubbles. The shards of volcanic glass of these three types are found in the resulting bentonites. Volcanic minerals occur as accessories, *e.g.* biotite, but quartz is uncommon and ferromagnesian minerals are scarce. The mineralogy indicates that the magmas giving rise to the volcanic ash were felspathic, similar in composition to latite.

The alteration of ash or tuff to bentonite takes place most readily in those rich in K_2O and Na_2O , but with only moderate amounts of Ca and Mg. The formation necessitates removal of SiO_2 and presence of salts of magnesium in ground-water, in lake, or salt waters. A necessary factor seems to be a leaching of the porous volcanic ash beds by water of alkaline character (pH 7 to 8).

The Ordovician bentonites, often referred to as meta-bentonites or K-bentonites, are also of volcanic ash origin, but their constituent clay mineral is a dioctahedral hydrous mica⁷, or a mixture of randomly interstratified 20% expanding, 80% non-expanding, clay-mineral layers. It is considered that the ash giving rise to these bentonites was similar to that of the pure montmorillonitic bentonites of Cretaceous and Tertiary age, but that the Ordovician volcanic ash was in contact with sea-water, in which it was deposited for a much longer period of time. This enabled the original Ca in montmorillonite to be replaced by K and a partial change from montmorillonite to hydrous mica to occur. The Ordovician bentonites of Norway appear to be of similar origin.

¹ *Journ. Amer. Ceram. Soc.*, **9**, 1926.

² W. C. Knight, Bentonite, *Engin. and Min. Journ.*, **66**, 1898, p. 491.

³ The Origin of Bentonite, *Wash. Acad. Sci. Journ.*, **7**, 1917, p. 196.

⁴ *Op. cit.*, 1926.

⁵ *Op. cit.*, 1945.

⁶ *Ibid.*

⁷ C. E. Weaver and T. F. Bates, *Clay Min. Bull.*, **1**, 1952, p. 258.

Fuller's Earth. Fuller's Earth is a clay which has a high absorptive capacity, used for removal of colour from oils and as a natural bleaching agent. The clay mineral present is generally montmorillonite, but may be attapulgite, as in the Georgia, U.S.A. earth. Some clays may be activated by acid treatment to act as Fuller's Earths¹.

Fireclay. Fireclays generally consist of hydrous aluminium silicates of the kaolin-type, often the 'fireclay mineral', a disordered kaolinite. As the name implies, these clays are used for production of refractory bricks, etc. Fireclays originate as residual clays (but are sometimes transported), e.g. in beds underlying coal seams, where they represent the leached material in which the coal-forming plants have grown².

Other Industrial Clays. Many properties are necessary in the use of clays as raw products for heavy industries and a detailed description of them is beyond the scope of this chapter. However, in a broad way, the environment in which a clay deposit was formed determines these properties, which may be related to a combination of minerals in a certain physical condition rather than to the presence of any single mineral. Thus it is found that clays belonging to certain formations are used for certain purposes. P. S. Keeling³ has summarized the four most important series of brickmaking clays in Great Britain as follows:

Carboniferous Clays	..	31 % of total output
Oxford Clay (Jurassic)	..	30 % of total output
Boulder Clay (Pleistocene)	..	9 % of total output
Keuper Marl (Triassic)	..	6 % of total output

FUTURE RESEARCH IN CLAY MINERALOGY

Clay mineralogy offers one of the most fascinating fields for modern research, one most profitable from the geological, pedological and mineralogical points of view. Tremendous progress in the study of clay minerals has been made during the last twenty-five years, due largely to improvement in X-ray equipment and techniques. Research is being actively carried out in most countries of the world and in many there are Clay Mineral Groups whose members meet regularly to discuss their investigations.

The realization of the importance of environment in the formation of clay-minerals had been expressed by many workers, but it was left to G. Millot⁴ to summarize and generalize from his examination of sediments from diverse environments. The elucidation of the physico-chemical conditions of clay mineral genesis is probably the most important contribution which can be made to the petrological study of sedimentary rocks.

¹ P. F. Kerr and P. K. Hamilton, Glossary of Clay Mineral Names, *Amer. Petrol. Inst. Prel. Rep.* 1, 1949.

² P. S. Keeling, *Trans. Brit. Cer. Soc.*, 53, 1954, p. 362.

³ *Op. cit.*, 1954, p. 13.

⁴ *Op. cit.*, 1949.

The position regarding clay minerals in soils is satisfactory, thanks to investigations of numerous soil scientists in all parts of the world; but much more detail needs to be obtained about the micro-environments in which rocks weather and soil-formation starts. A promising field is in the study of individual soil-profiles, where there may be changes in the type of clay mineral caused by development of the horizons in the profile.

Pure samples of kaolinite and montmorillonite are easily obtainable for detailed structural and chemical examination, but others, such as the hydrous micas (illites), chlorites, chamosites, etc., are not, and methods of concentration and purification are required. It is probable that improved methods of electrophoresis may be able to supply that need. Until detailed studies of these minerals, comparable with the structural and chemical analyses of C. S. Ross and S. B. Hendricks¹, and those of M. D. Foster² have been made, our knowledge will not be adequate. The occurrence of regular and irregular interstratified mixed-layer minerals requires further investigation. Certainly the naming of new minerals should never be undertaken without adequate experimental data.

The colloid chemistry of the clay minerals has been extensively investigated by C. E. Marshall³ and his co-workers, using a member of the montmorillonite group as the principal research material. It is at present only partially predictable to what extent both kind and quantity of cations can be adsorbed by clay minerals. The fixation of certain ions, *e.g.* potassium and ammonium, has been studied, but much additional information is required. Anion exchange requires further investigation. The exchange capacity and its relation to environment of formation of all types of clay minerals is probably the most important field for future research. Ion-exchange is an important factor in the genesis of clay minerals from rock minerals (such as feldspar); it is responsible for changes taking place in clay minerals in soil-profile development and in various other environments. Exchange capacity serves to explain the presence of particular types of clay minerals in the Great Soil Groups and in soils subjected to minor local variations.

Future research in clay mineralogy can therefore be summarized as follows:

1. Physio-chemical investigation of the environment of clay minerals (this to include all cation and anion exchange phenomena); rock-weathering; soil formation.
2. Structural and chemical analyses of clay minerals so far not thus analysed, *e.g.* hydrous micas (illites), chlorites occurring in sedi-

¹ *Op. cit.*, 1945.

² *Amer. Miner.*, **36**, 1951, p. 717; **38**, 1953, p. 994.

³ *Trans. 4th Inter. Cong. Soil Sci.*, **11**, 1950, p. 71.

mentary rocks, soils and other environments (this will necessitate concentration of different types of clay minerals by various means).

3. Investigation of mixed-layer clay minerals.
4. The distribution of clay minerals and their evaluation in certain situations as indicators of genesis.
5. Occurrence and diagenesis of clay minerals in sedimentary rocks.
6. Relationship of clay minerals to various other minerals in their environment.
7. Minor element distribution in clay minerals.
8. Stability of clay minerals in acids, alkalis, etc.
9. Relationship of clay minerals to organic matter.
10. Stability of clay minerals during transportation.

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CHAPTER IV

THE PRINCIPLES AND PRACTICE OF DIFFERENTIATION AND COR- RELATION OF SEDIMENTS BY PETROGRAPHIC METHODS

The Geographical Cycle—Provenance—The Distributive Province—Conditions of Deposition—Technique of Application of Petrographic Methods—Schedule of Information required from Heavy Mineral Assemblages—Deductions from Records—Special Cases in the Application of Petrographic Methods to Correlation and Differentiation Problems—Thin Section Correlation of Consolidated Sediments—The Study of Accessory Minerals in Igneous Rocks.

GEOGRAPHICAL CYCLE

THE basic principles underlying the technique of differentiating or correlating strata by means of their stable mineral components are essentially those fundamental to the science of geology. No new or fantastic theories have had to be invoked to support their validity in this connexion or their use in this particular application to determinative stratigraphy.

These principles are practically all embodied in the modern conception of the geographical cycle, in its geological interpretation. Briefly stated, the cycle implies terrestrial uplift of a base-levelled or peneplained region; consequent reanimation of the forces of denudation; their slow operation in wearing down this newly-formed land-surface and the persistence of these forces until a new base-level is once more attained. The complete cycle is thus a geological episode and modern stratigraphy owes much to the recognition of these periodic recurrences. Expressed in another way, it is the alternation of geosynclinal and orogenic phases of earth-history.

Now this kind of cycle of geological events can, for our purpose, be broadly construed as a cycle of sedimentation. The newly uplifted land-mass, composed of igneous and/or sedimentary rocks, undergoes subaerial denudation and from the very first incident of destruction gives rise to a new sediment. With continued disintegration of the mother-rocks there is built up a collateral sedimentary deposit derived therefrom; so the process

matures with the achievement of the base-level phase, assuming no interruptions of a diastrophic or similar disturbing character. Thereafter this newly formed and, by this time, consolidated sediment itself becomes involved in orogenic movements and, probably rent and deformed with igneous intrusions, rises to initiate the next cycle of sedimentation.

Naturally the conditions under which such cycles are achieved vary widely under the influence of climate and the area of the earth's surface affected. We may contrast the normal cycle as outlined above with the arid cycle determined under desert conditions; also the results of upheaval of a comparatively restricted area of a continent with those accruing from a widespread orogenesis which, like the great Alpine movements, encircles nearly half the globe. In this work it is important to keep both such perspectives in view. But whatever the magnitude of the cycle under investigation, whether in space or in time, the simple principles which it implies constitute the foundation of our work and should be kept constantly in mind.

PROVENANCE—DISTRIBUTIVE PROVINCE

It is necessary to examine the component factors of the sedimentation cycle in further detail. First of all the newly uplifted land-mass; this, or the rocks of which it is composed, is essentially the *provenance* of the sediment formed by its denudation. The term *provenance* implies source of origin; but, in addition, it has been found convenient in petrographic work to introduce some qualifying definition which enables that source to be visualized as a geological entity. The term 'Distributive Province'¹, first introduced by A. Brammall, has been generally adopted and implies the environment embracing all rocks, igneous, metamorphic and sedimentary, contributing to the formation of contemporaneously accumulated sediment. It is essentially the rocks of the distributive province which, on weathering, yield up their minerals, the stable species to survive rigours of chemical reaction and mechanical transport, the unstable components to perish. The more diversified the rocks of the distributive province, the more variable the sediment formed from it. In some cases the province may be entirely sedimentary; this implies that the sediment formed receives its constituents second hand; in other words, it represents redeposition of a pre-existing sediment. By contrast, disintegration of igneous rocks furnishes primary sediments.

Conversely, accessory minerals of a sediment, sometimes individually, generally collectively, constitute a measure of its provenance, leading to a reconstruction of the nature of the distributive

¹ In H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 366.

province even though all traces of this may long since have disappeared. This is because certain minerals or groups of paragenetic species are inferential of definite rock-types. Thus the reciprocal relationship between provenance and sedimentary rock is always kept in view in this work.

The next factor concerns the transference of released mineral matter from parent-rock to basin of sedimentary accumulation and the circumstances in which such transference takes place. Two important influences exert control; the mechanical agency or medium of transport is one; chemical destabilization, the tendency of many rock-forming minerals to undergo decomposition when released by denudation, is the other. Mechanical forces, whether wind, water or ice, largely determine the ultimate physical forms of the derived mineral grains; to these forces such inherent properties of minerals as hardness, gravity, cleavage, etc., react in different ways according to their fundamental molecular constitution; shape and size of mineral particles are likewise functions of them. Chemical weathering attacks the less stable rock-forming minerals, which are thus decomposed, formed into secondary products and dispersed in solution, finally to reappear in most cases as authigenic constituents. Every sediment bears the impress of this destabilizing environment to a greater or lesser degree; it is essentially its sifting influence which tends to restrict the number of critical heavy minerals which survive, thus enhancing their indicative value.

Neglecting for the moment the time-factor required for this transference of material, it will be clear that successive phases of denudation will promote corresponding phases of sedimentation. If this is reduced to the mathematical conception of plane-surfaces, then we can imagine an infinite series of denudation planes having their counterparts in equivalent sedimentation planes. Thus the accumulation of a given thickness of sediment will represent the destruction of a corresponding and directly related thickness of parent-rock.

Now if the original parent-rock is homogeneous in composition throughout the cycle of erosion, then it follows that a sediment equally homogeneous in composition will result, *ceteris paribus*. But if the parent-rocks vary in composition with progressive denudation, so the contemporarily formed sediments will indicate, by change of stable accessory minerals, such inherent variations of provenance; the sediments will, in fact, themselves exhibit mineral variation to a corresponding degree, which thus becomes characteristic of them. If there is definite mineral variation in a given thickness of sediment, then recognition of the degree of that variation and of the planes or horizons at which it takes place

furnishes criteria of subdivision of that sediment. This, then, is the basis of differentiation of sedimentary deposits by means of stable, chiefly heavy mineral, variants.

It further follows that if these heavy minerals have any potential value as indices of differentiation or correlation of the sediments to which they are indigenous, they must, like fossils, have a reasonably restricted range in space and time, especially the latter. This depends again on the rocks of the distributive province; the more varied in mineralogical composition these are, the more definite and restricted will be the sedimentary mineral zones.

The comparison between detrital minerals and fossils, however, is a dangerous one and cannot be pushed far, principally for the fact that mineral species, unlike fossil species, do recur after temporary 'extinction', similar groups of minerals reappearing time and again throughout the geological record, but, as will be shown, not in such a way as to vitiate their use in each special circumstance. Notwithstanding this, the simile is a convenient one providing it is not unduly stretched. Actually, mineral 'zones' are seldom sharply defined; gradual transition (in a conformable series of strata) is the more general condition proved; this state of things is conveniently illustrated in the diagrams (Figs. 65, 66).

CONDITIONS OF DEPOSITION

A, B, C, D, E and F (Fig. 65), represent different rock-types in two distributive provinces (1) and (2) respectively. The initial denudation of (1) and (2) starts, probably, with C and F respectively; the first types of sediment to be laid down (C' and F') will therefore have decided C and F affinities. As the drainage is cut back, B and E contribute material, the transition being marked by sediment with bC and eF affinities respectively (the smaller letter in each case denoting the lesser influence). With the progressive advance of denudation, both B and E assume importance, with the result that

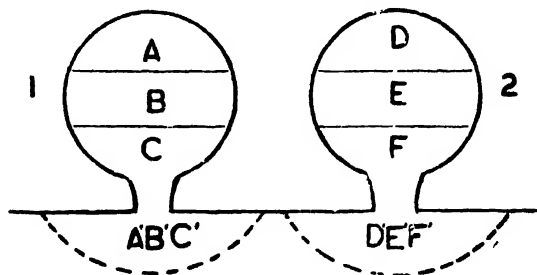


FIG. 65. Distributive Province Diagram.

still newer deposits B' and E' are evolved. Similarly A and D contribute the deposits A' and D' respectively. Ultimately vertical sections in the newly formed deposits will disclose successions as indicated in the diagram (Fig. 66), bC', aB', eF' and dE' being the transitional zones from one horizon to another.

Contrasted with such vertical differentiation of sediments is the important and, in many respects, more difficult application of heavy accessory minerals to areal correlation, *i.e.* the comparison of these indices from place to place and assessment of their similarity or dissimilarity as a basis of correlating the sediments to which they

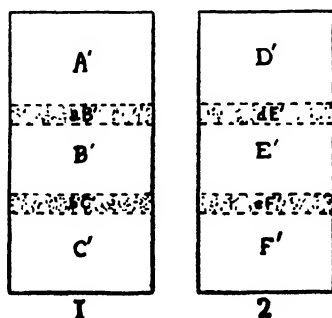


FIG. 66. Vertical Sections and Mineral Zones.

pertain. Examples are furnished within limited areas by the comparison of samples from a series of wells on a given oilfield where, perhaps, only a few square miles of a formation are concerned; or over a much wider area, by comparison of samples collected from isolated outcrops or from different points across a long stretch of country. Whatever the area involved, however, the guiding principles are the same as before, with the addition of one uncertain factor: the vagaries of spacial distribution of material. This requires explanation.

In the case of differentiating sediments in vertical succession as described, we are dealing with a restricted column of rock in which the chances are most favourable to the manifestation of every variation, however subtle or striking. With lateral correlation, a vast area has to be explored (comparatively) and variations which may or may not be entirely due to the influence of parent-rocks have to be taken into account.

So long as one fairly definite distributive province has been laid under contribution, the formation may be expected to carry distinctive mineral characters throughout its entire development; comparison of samples from different places will tend to show

mechanical rather than mineralogical variation. The reason for this is to be sought in the original distribution of material during the phase of sedimentation concerned. Now distribution is to a large extent independent of the nature and provenance of detritus and as it affects the present conception, it is not solely a question of mechanical agencies of transport. The actual medium in which the material is distributed is of equal importance.

Consider marine conditions. Distribution of sediment, apart from land-drainage, is controlled by the ocean, its currents and their directions; the width and configuration of the continental shelf; depth of water; magnitude of the sedimentary load; size of particle; physiographical factors; climate, etc. Along any one time-plane lithology may change rapidly; the stable 'heavy' mineral supply may become impoverished; the grade-size of the sediment may diminish so considerably that recognition of an anticipated mineral suite may be almost impossible. Yet these are the conditions normally encountered.

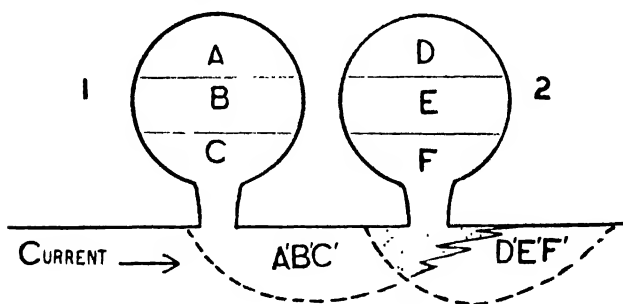


FIG. 67. Influence of Current-Action on Deposition.

Again, the conception of two or more distinct distributive provinces, contributing their quotas of material to sediment accumulating in a common basin, is very real; present-day examples of this are numerous; similar circumstances have clearly operated constantly in past geological history. Under such conditions there is continual intermingling of different mineral suites; at some stages one suite predominates, at others, another; equally there will be periods when each exerts a similar amount of influence. Or it may be that the drift of sediment, the product of one particular province, may determine intermingling with the product of another province geographically far removed, while beyond the zone of drift, the product of the latter province may occur exclusively. All three sediments co-exist in a common basin, the two distinctive products and their compounded elements in the 'overlap' zone. They may clearly be contemporaneous in point of time and

will probably be characterized by a common fauna throughout. It is essentially the mineral composition which will vary and, in such an example as this, to an extent which practically vitiates any correlation over large areas. It is for this reason unsafe to push the application of petrographic methods too far in areal stratigraphy and to this extent the limitations of the technique must constantly be borne in mind. The principles discussed in this connexion will perhaps be more firmly grasped by means of the accompanying diagram (Fig. 67).

This shows the prevalent current travelling in a direction from the first to the second province, parallel to the shore-line. While the sedimentary series $A'-C'$ would preserve local individuality, its lateral displacement due to the current would cause contamination of and interdigitation with the series $D'-F'$, indicated by the shaded area in the figure. Thus in specific cases the composition of the mixed sediments might be represented by $c'F'$, $b'E'$, etc., c' and b' connoting the introduction of material from the first province. Beyond the zone of mixing, sediments $D'E'F'$ preserve their fundamental characters; clearly the mineral composition of $A'B'C'$ may be vastly different from that of $D'E'F'$, yet assuming contemporaneity of deposition, they are theoretically correlative on any other grounds.

TECHNIQUE OF APPLICATION OF PETROGRAPHIC METHODS

From the foregoing exposition of first principles, we may now turn to a consideration of the technique involved in their application. At the outset a word of warning is necessary. As in most other branches of specialized science, experience counts for everything. However well the theoretical aspects of the subject may be assimilated, nothing but complete mastery of the method and scope of investigation will lead to success. The first essential is proficiency in diagnosis of minerals as detrital grains. This will be found a vastly different proposition from familiarity with such minerals as museum specimens or constituents of rocks studied by means of thin sections.

The cult of the detrital mineral is well worth following; apart from its obvious application to problems in economic geology, its study opens up a wealth of interest, especially when the natural history of a sediment is the motive of the work. But it is necessary to begin at the beginning. Competent diagnosis of detrital minerals, from the ubiquitous quartz to the rarest species, springs only from continual study of examples from as many different sources as possible. Only in this way can the innumerable variations of detrital minerals be learnt and accuracy in application achieved.

The beginner is advised to procure for himself a set of microscope slides of the commoner sedimentary rock minerals—concentrates of individual species—and to study these exhaustively. A good list to start on is as follows: *quartz, microcline, glauconite, calcite, ilmenite, pyrite, leucoxene, tourmaline, staurolite, garnet, rutile, zircon, muscovite, biotite, kyanite, andalusite, topaz*. Two or three mounts of each species from different geological horizons should, if possible, be obtained and thus certain variations appreciated. The choice should also be made with a view to selecting concentrates of different grade-sizes, so that the minutest particles may receive as much attention as those of larger dimensions. In each instance learn the essential crystallography first. Study the normal crystal habits of the mineral with a good text book of mineralogy and then with the aid of the information detailed in Chapter I of this volume, work out the nature and degree of detrital modification.

To the science of crystallography many students do not hesitate to express a certain apathy; there may be something to be said for this, but the author hastens to assure the reader that it implies an intelligent use of the text book and an understanding of the elementary principles of the science, especially as regards the optical physics involved; 'stereographic projection' and the higher mathematics of the subject are not necessary for this particular work; relieved of that, crystallography can be made a most fascinating study, doubly accentuated when it is correctly applied to the reading of mineral grains under the microscope.

From the study of individual mineral concentrates as suggested, procedure should be in the direction of detrital mineral suites isolated from well-known stratigraphical units. In this connexion a selection might appropriately be made from the Inferior Oolite, Corallian, Lower Greensand, one of the Lower London Tertiaries, e.g. Thanet Sands of the London Basin, the Bagshot Sand, Pliocene sand from East Anglia and any drift deposit; good examples of the latter occur in most of the plateau deposits of the home counties. Additionally an alluvial sand, a desert sand and a glacial sand should be obtained for the study of contrasted shapes of the particles in each case. With this as foundation, no time need be lost in proceeding to the more uncommon minerals, either studied as individual concentrates or as constituents of specific mineral assemblages. Moreover, throughout the training, learn to exact the fullest powers of the microscope; on its efficient employment depends the difference between crude and really competent work.

The next stage is an attempt at differentiation of two well-known stratigraphical formations. Comparison of any two slides of the total heavy residues from examples above suggested will indicate

at once the variations which serve to distinguish them. Those whose facilities do not extend to investigating British formations in this manner, are advised to choose any two well-known deposits in their area, preferably two separated by a considerable geologic time-interval; thereafter this interval should be gradually reduced until the investigations concern horizons in the same formation. It will probably be found that it is this phase of the work which presents the first real difficulties. Even the novice seldom fails to recognize essential differences between mineral suites of two widely separated (in time) deposits; it is the splitting up of a 'straight sequence' of beds within one stratigraphical unit which calls for experienced observation and deduction.

From differentiation of beds in vertical succession, attention should be turned to a simple problem of correlation, say, the examination of a series of samples collected from isolated outcrops of a known formation, or from three or four outliers, etc. A further valuable test is to trace the variation through a deposit along the strike over some distance (say, 50 miles), keeping to a constant horizon either lithologically or, better still, palaeontologically determined. This should be supplemented by similar work over wide outcrops in directions at right angles to the original shoreline.

Investigation of subsurface rock-samples is but a particular case of the technique of differentiation and correlation by accessory minerals, but with this important difference; whereas with surface work the rocks themselves, their lithology, developments and structures in which they are involved, are all exposed to the eye (and to this extent is their investigation facilitated), rocks studied by means of borehole samples may lie deeply buried under younger deposits or a thick covering of drift, hidden for all time, or possibly outcropping many miles away from the area concerned. This is especially the state of things prone to occur in oilfield geology, wherein these petrographic methods still find one of their most valued applications. This kind of subsurface stratigraphical research requires the highest degree of skill in handling mineral residues for differentiating a vertical sequence of samples furnished by numerous oil-wells; in comparing them *areally* at known depths (correlation) so as to trace out the attitude of an important stratum; it also calls for intelligent and restrained deduction as a basis of defining subsurface structure.

The latter problem is frequently the most difficult of all. It cannot be too strongly emphasized that incompetent work with heavy minerals leads to disaster more rapidly than any other known weapon of attack in the geological armoury; a careless mistake in identification or an incautious interpretation of microscopical analysis may easily lead to costly error, a matter of no

small moment in the economics of petroleum development. But perhaps of more importance is the harm done to the science by such slovenly work. Unfortunately, examples of this are not wanting and in more than one instance known to the author heavy mineral methods have earned a measure of opprobrium which they little deserved.

In petrographic methods biassed to this particular line of enquiry, the personal equation looms large. No two operators work on precisely the same plan and what may appear to be subtle though convincing proof of distinction to one, may be passed over in favour of alternative evidence by the other. This, from the very nature of the investigations, is bound to be the case. In most branches of analytical geology there are more ways than one of arriving at the accepted conclusion. After all, the main thing is to achieve accuracy; the actual method of attaining it matters little so long as it is scientific and is fully justified by the principles laid down. The reader has only to compare different published accounts of heavy mineral analyses and correlation to perceive the truth of these remarks.

Accordingly, in such circumstances no hard and fast rules can be laid down in the actual process of differentiation and correlation by these methods, nor would the best interests of the work be served by any attempt to standardize technique. On the other hand, experience has taught a certain routine which has been found satisfactory and adequate to every problem worked out over many years by the author. It has the merit of being straightforward; it does not imply an inordinate amount of time to achieve results; it does not attempt the impracticable task of reducing mineral assemblages to mathematical formulae; and it may be claimed to be sufficiently elastic to meet every contingency in which the methods may be invoked. The reader will not go far wrong if he follows along similar lines; doubtless, when he has acquired his experience, he will be able to make many improvements in detail.

Starting with the microscope slides of the minerals under investigation, two courses are open, according to the nature of the work. If it is to be exhaustive and time is not an important item, three slides per sample should be made. One of these is the original sediment, either in its natural state, if incoherent, or gently pulverized, if consolidated. The second is a mount of the cleaned, light sediment (*i.e.* S.G. <2.9, usually the 85-52 sieve fraction (B.S.I.)). The third is the total 'heavy' residue. The object of this triplication is to safeguard against loss of any soft or soluble mineral during the process of cleaning the sample, etc. Also, many instances occur where the light minerals are as important, if not actually more so, than the heavy constituents.

Where, however, previous knowledge of the sediment discounts the chance of the light minerals serving useful purpose, or where, as in much economic work, time is a vital factor, then the light and original mounts may be dispensed with and investigations proceed entirely on the basis of the heavy mineral residue. The operator must use his own discretion in the matter.

Triplication of slides necessarily implies much additional labour in preparation, but actual microscopical examination of the light crop and original sample takes only a fraction of the time occupied with the heavy residue. In the author's view, if the light minerals are neglected altogether, there is always the feeling that some important feature has been passed over, that the sudden influx of minute organisms, or minerals like feldspar or glauconite, has been missed, when any one of these components might have proved valuable.

The practice of isolating magnetic and non-magnetic crops of minerals and employing separate mounts for each, while sometimes essential in academic research, may be found impracticable in economic work; the total heavy residue, or a proportionate part of it, is then the basis of comparison. It is often difficult to carry in mind the salient features of several assemblages when attempting their differentiation, especially if the number of samples is large, a difficulty much enhanced by duplicating every slide. This has reference entirely to economic work; as stated above, where time is no object and where the most detailed investigations are contemplated, circumstances are altered and even six slides of one sample, two high gravity concentrates in addition to original, light, magnetic and non-magnetic crops, may be essential. The author has had occasion to use a dozen mineral segregations (each involving special preparation and an equal number of mounts) from one concentrate in order to reach exhaustive quantitative and qualitative results from certain special samples.

SCHEDULE OF INFORMATION REQUIRED FROM HEAVY MINERAL ASSEMBLAGES

The slides of the respective mineral residues to be examined are first sorted out in some definite order, according to depth (oil-well or water-boring samples), geographical or other position (field-samples), or in numerical order if there is nothing else to determine the arrangement. Next, every slide in succession is rapidly examined under the microscope, any striking similarities or dissimilarities being segregated at the outset into groups. [N.B.—It is convenient to use a series of cardboard specimen-trays, about 4 in. × 5 in., to accommodate each group of slides.] The groups

form the basis of subsequent methodical examination, leading to confirmation of the initial segregation and to further subdivision of the slides, hence of the samples they represent. The object of this preliminary 'run through' is to enable one to grasp at the outset the main features of the mineral suites; much may be discernible in the process; it is seldom that it is not so. But at least a valuable first impression of the problem ahead is gained and for this reason, if for no other, this preliminary survey is desirable. To work diligently through, say, two hundred well-sample residues (by no means an uncommon job in an oilfield laboratory!) without any idea what the two hundredth is like until, at long last, it is ultimately reached, can prove a most disconcerting performance.

The following schedule of information is next sought:

- (1) Identification of minerals.
- (2) Notification of minerals with special crystallographical features (other than accidental occurrences).
- (3) Notification of minerals with special physical features (other than rare occurrences).
- (4) Notification of minerals with special optical properties.
- (5) Relative frequency of occurrence of individual minerals.
- (6) Reciprocal relationship between two or more prominent minerals.
- (7) Grade-size or sizes of predominant minerals present.
- (8) Average shape of prominent (common) minerals present.
- (9) Any particularly striking feature (or mineral) sufficiently prominent to constitute an index of the sample concerned.
- (10) Character of total assemblage.

The schedule in itself looks somewhat formidable, but in actual practice the experienced operator checks up this information almost subconsciously and enters it on his record, at the same time carrying in his memory the salient features, of whatever nature, of any unique or striking assemblages examined. A facsimile of the form devised by the author for recording this information is illustrated in Fig. 68, p. 384.

For the benefit of the novice, the ten items in the above schedule are here annotated:

(1) *Identification.* In view of what has already been written on this point, little remains to be added. Diagnosis can never be too thorough and the greatest accuracy is absolutely essential. In some cases, 100% identification may be impossible, especially with very fine grade sediments; in other cases a problem mineral may present itself which defies positive diagnosis in the time or with the facilities at hand. If such a mineral is adventitious, occurring in

one or two samples only, it may probably be neglected with safety; if it ranges through a number of associated samples in such a manner as to constitute a feature of those samples, then it is necessary to recognize it by some make-shift designation, e.g. 'Mineral X'. Ultimately, of course, the enthusiastic worker will not be content until he has found a mineralogical 'value' for 'X' (Vol. I, p. 254). A further point to note is that a mere list of mineral occurrences is *per se* seldom of much value; it is the rest of the qualifying information, covered by the schedule, which determines its utility, a remark applying equally to mineral residues segregated from crushed igneous rocks (see p. 410). For further aid in diagnosis, see this volume, Ch. VI.

There is no particular order in which minerals should be determined or recorded, though there is some convenience in listing light species first, followed by the iron-ores, then by the common non-opaque minerals, working down to the scarce occurrences at the bottom of the list. In published records, however, the arrangement of the minerals by crystal systems has much in its favour (this volume, p. 19)¹.

(2) *Special Crystallographical Features* include well-preserved crystals of a mineral (euhedral); striking development of subsidiary faces (e.g. the 'facetting' of zircon); prominent terminations (e.g. acute bipyramids); twins (e.g. geniculate twins of rutile); also striations, zoning, inclusions and any obvious inherent structures. Any prominent varietal features of a given mineral traced through a series of samples may quite likely result in turning the scale in favour of their correlation. In other directions, varietal features of minerals have decided bearing on questions of provenance². Inclusions, especially in quartz, are of value in determining parent-rocks³. Even absence of crystallization may, in some cases, prove a valuable characteristic of some prominent species.

(3) *Physical Features* amenable to microscopical determination concern chiefly colour, lustre and grain 'morphology'. Colour, or its absence, is an important criterion of identification. Colouring matter may be uniform or partial; for instance, some sapphire grains are uniformly blue, others from different sources have their colour dispersed in patches, giving a blotchy appearance (see frontispiece). Parti-colouring (e.g. brown-green tourmaline) may prove a distinctive feature. Vivid colours are noteworthy since most detrital minerals exhibit somewhat subdued colouring. A

¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 75, 1909, p. 231.

² P. G. H. Boswell, *Miner. Mag.*, 21, 1927, p. 310; also A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 48.

³ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 260.

definite coloured mineral, *e.g.* purple zircon, may prove a critical indicator of a deposit, equally of its provenance¹. A common mineral occurring in an uncommon colour would constitute a valuable index of the samples in which it was found, *e.g.* naturally pink andalusite, green garnet. Lustre, determined by good artificial incident light, needs no stress here.

Grain 'morphology' is a convenient expression to describe the external form of mineral-fragments. It is not merely a record of shape and size, though these properties could appropriately be classed in this category (see (7) and (8) below), but rather the structure of the grain, the contrast between acicular and granular developments, between fibrous and crystalline, etc. Examples in which grain morphology has proved critical in differentiation are the temporary appearance of actinolite (fibrous hornblende) at one horizon of an amphibole-rich deposit; granular titanite as characteristic of a zone in a deposit otherwise marked by ragged, irregular grains of the same species; also the co-existence of spheroidal and irregular grains of siderite.

(4) *Optical Properties* of minerals, especially where they are of an unusual character or of pronounced development, are among the most important criteria of distinction. Refractive index, birefringence, pleochroism and the nature of the interference figure (if any) are the four most sought after features. Refractive index, as indicated by relative 'relief' to the medium in which the minerals are mounted (usually Canada balsam), is probably the most important first impression in diagnosis. With practice it is surprising how closely this can be assessed from microscopical observations, especially if several different mineral species are present, some immediately known, others unknown until thoroughly searched. Birefringence is all important in diagnosis if it can be accurately determined on mineral grains; this, however, is not always possible with dense or deeply coloured grains. Normally pleochroic minerals vary considerably in intensity of pleochroism: this constitutes the criterion and many examples could be given. Among the best from the author's notebooks are the intense blood-red pleochroism of andalusite from the Cornish Pliocene; the vivid brown-green pleochroism of hypersthene from a Quaternary sand of Martinique; the deep mauve pleochroism of glaucophane from certain Miocene silts of Trinidad and Venezuela; the olive-green to slaty blue pleochroism of chloritoid from the Bridport Sands of Dorset. In each case the striking colour-change distinguishes the mineral, which in turn distinguishes the samples in which it is found. The examples could be multiplied many times;

¹ P. G. H. Boswell, *op. cit.*

some of the best minerals in which to anticipate unique or distinctive pleochroism, apart from those mentioned above, are the amphiboles, tourmaline and staurolite.

In the matter of interference figures, the maximum information obtainable from these depends on ability in their interpretation. The mere observation of uniaxial or biaxial character is seldom of more than slight diagnostic value; an exception is the occasional occurrence of undoubted biaxial zircon; this would certainly prove indicative of the samples in which it was found. The kind of optical research implied is well illustrated by A. Brammall's work on Dartmoor brookite¹ and as demonstrated by that author, it connotes nothing less than careful optical measurements, observations of the behaviour of the figure, in particular its colour-bands, on rotation, etc. Those who possess sound knowledge of optical physics know how to appreciate and to use this valuable weapon, not only for diagnosis, but for running down a mineral which, apparently normal and of no index-value, becomes critical on account of some determined optical peculiarity; lack of such knowledge renders the observation both empirical and mechanical and constitutes a serious disadvantage in this kind of research. Other examples of critical interference figures of detrital minerals from the author's experience are the comparatively large axial angle of some black mica ($\pm 30^\circ$) suggesting phlogopite (diagnosis not apparent from the mineral itself); very large axial angle in some muscovite flakes; some basal quartz grains which show abnormal 'splitting' of the cross on rotation; the eccentric, partial interference figure of a deeply coloured epidote; the optical characters of brookite, axinite and titanite; certain varieties of topaz with smaller axial angle than usual and very prominent crimson colour-bands.

(5) *Frequency*. If there still persists a mild 'bone of contention' among petrographers, it concerns methods of estimating, still more of reporting, relative proportional occurrences of minerals in a given assemblage. All are now agreed that frequency statements, if accurate, have considerable stratigraphical value. In work on differentiation and correlation of sediments, this value is unquestionable. The problem is, how to arrive at an accurate expression without depending too much on purely visual assessment or without going to the other extreme of counting grain by grain by eye, truly a heart-breaking process. Fortunately, the introduction of the automatic point counter (Vol. I, p. 281) has largely overcome this difficulty.

Probably most frequency estimations are by eye, and after continual practice it is, in the author's opinion, possible to arrive at

¹ See this volume, p. 64.

reasonable results, providing the grade-size of the suite is not too small. The finer the grade, the greater the inaccuracy of assessment, assuming a good quantity of residue. Scanty residues in any case lend themselves more readily to accurate estimation and even counting is then not too onerous. But no two estimations by different persons ever agree. The author in the past frequently tried this out with his classes of students and it is surprising what variations exist in apportioning powers. What is abundant to one, is merely common to another; the tendency to attribute predominance to opaque minerals, because they show up sharply against a white background, is another source of error. The conclusion is forced that, except in the circumstances of limited residues of large grade-size, estimation by eye is really inaccurate, therefore of little value.

At the other extreme we had several years ago the original work of W. F. Fleet¹, who, in the course of his researches into heavy minerals in rocks of the English Midlands, found that nothing short of counting the grains of a residue gave satisfactory results. He writes, ' . . . to obtain accurate results that may readily be compared with those of other workers actual counting of the grains is considered essential . . . at first sight, a tedious task, but it has been found that, using, say, a $\frac{1}{16}$ in. objective with an eye-piece giving a large field, and by employing a mechanical stage, it is not a difficult matter to traverse the whole width of a slide several times, counting every grain. According to the closeness with which the minerals appear on the mount it may be necessary to count the grains in anything from twelve to fifty fields, and the number of grains may range from 500 to 1,000 or even more.'

Most petrographers have since had recourse to counting and their work has abundantly confirmed the findings of W. F. Fleet. The superiority of counting is unquestioned. Where reliable quantitative results of proportional occurrence of each species are demanded, nothing short of counting is likely to give satisfaction. In our special work, this is definitely the case where the fundamental mineral assemblages from different horizons of a formation are not rich in species or varied; where, in fact, the same minerals tend to occur throughout, and differentiation perforce rests on less obvious variations and on relative frequency of occurrence². In cases where the mineral differences prevailing in two deposits are sufficiently striking, the frequency factor may assume

¹ *Geol. Mag.*, 63, 1926, p. 505.

² A good illustration of the use of relative frequency of heavy minerals to find the necessary criteria for differentiating one sedimentary deposit from another is given by D. R. Derry in his account of the Pleistocene beds of the Don Valley, Toronto, Ontario (*Journ. Sed. Pet.*, 3, 1933, p. 113).

less consequence and qualitative estimation by eye suffice. But since much work carried out today necessitates some numerical expression of frequency, then it is clear that counting is inescapable.

Even precision counting, however, may have its 'snags'. F. Smithson¹ has drawn attention to the significance of the manner in which heavy mineral concentrates are prepared, those made by panning not being identical with those obtained with bromoform, or again where panning the 'light' material and completing the separation with bromoform is involved (see Vol. I, Ch. III, p. 114). Actual experiments with heavy mineral counts made on samples from which concentrates had been prepared *with* and *without* the use of panning (using in all cases bromoform) showed that divergencies are much greater in practice than might be anticipated. For example, in one case a zircon and monazite (combined) count gave 80% when the concentrate was prepared by first panning and then bromoform separation, and only 56.1% when bromoform was used direct. Assuming the latter method to yield the true value, then the advent of panning gives a result 1.68 times too great!

When it is considered that panning is so frequently employed, either solely where conditions do not permit of heavy mineral separation, or as part of the process of concentration where bulk samples have to be reduced to manageable size, then it is abundantly clear that even percentage frequencies of grains are not comparable as between one worker and another *unless their modus operandi is identical*. As F. Smithson says, 'So long as a petrologist always employs the same procedure it is probably safe for him to compare his estimates one with another. But if he changes his method or compares his estimates with those of petrologists who use different methods of separation, erroneous conclusions may easily result.'

A. L. Dryden² reviewed this technique from a critical and statistical angle. He showed clearly that mere counting is not accurate because it expresses percentages rather than qualitative observations as to 'scarcity', 'abundance', etc. He rightly pointed out that the problem is first one of *sampling* error. If correlation of strata is to be based on relative percentage (heavy mineral) frequencies, then the assumption must be made that an *average sample* from the deposit has been initially obtained and that the heavy mineral concentrate prepared therefrom is typical of that sample. How often is this really the case? From a mathematical aspect, A. L. Dryden demonstrated that accuracy in heavy mineral counting increases as \sqrt{n} , when n = the number of grains counted,

¹ *Geol. Mag.*, 67, 1930, p. 134.

² *Proc. Nat. Acad. Sci.*, 17, 1931, p. 233.

actually *less* than the total number of grains (heavy or light) mounted on the slide under examination. Thus, 'if twice the accuracy is desired, 4 times as many grains must be counted; if 3 times the accuracy, 9 times as many', etc. 'The law of diminishing returns' probably will make us content to count but a few hundred grains. Perhaps 300 will suffice for most ordinary work, and even then the accuracy will far transcend that attained by estimation.' The same author stressed that the worker should be cognisant of errors inherent to such counting analysis and that a degree of accuracy must not be indicated or implied which is, *a priori*, greater than genuine. He deduced in one case, where a particular mineral composes 50% of the sample, that to achieve an accuracy of 1/10th of 1% which has been implied by certain published 'counts', the colossal number of 454,950 grains would have to be counted! Thus 1% accuracy implies a count of 4,549 grains in a similar case, whereas a normal count (say 200 grains) implies only 5% accuracy.

Variation in heavy mineral percentages in samples taken from different localities is obviously both possible and normal, hence counting grains to a recorded accuracy of less than 5% error is clearly a waste of energy. From this follows the logical manner of expressing frequency obtained by counting, *viz.* the apparent value $50 \pm 13\%$. From this it further follows that the petrographer must state the method he has used to arrive at his percentage frequencies and 'that the reader will not be misled into assuming that, for example, 58.1% means 58.1%, when it might as well be 50 or 70%'.

In a well-reasoned statistical essay on comparison of heavy mineral suites, A. L. Dryden¹ emphasized the distinction between 'correlation' as implying synchrony of geological formations and determined by, say, palaeontological data and 'heavy mineral correlation' which, as he demonstrated, is 'an entirely different concept, although the process may lead to results quite analogous to those attained by the use of fossils'.

Heavy mineral correlation, he argued, must rest on comparison of one heavy residue with another and mere segregation of impressions into 'like' or 'unlike suites' is not enough. If such correlation is to be based on inspection of percentages (resulting from 'counts') of heavy minerals in different samples, there must be some method of 'seeing these relationships quantitatively'.

'For what we really mean by "heavy mineral correlation",' says A. L. Dryden, 'is that for two given rocks containing similar mineral suites, the net result is *as if* the distributive province, mode

¹ A Statistical Method for the Comparison of Heavy Mineral Suites, *Amer. Journ. Sci.*, 29, 1935, p. 393.

of transportation, environment of sedimentation and other factors had been the same in the two cases. Such a supposed concatenation of events leading to similar mineral suites we think of as more likely to have happened in the two places at the same time. And the closer the samples be geographically the more favourably we look on such a theory. The whole method, then, is based on the degree of similarity of mineral suites—great similarity leading to the inference that the same cause has been at work in the two or more samples and dissimilarity implying independent (and thereby, in a single basin of deposition, non-synchronous) origin. And yet we have no way of expressing similarity except by juxtaposing columns of percentages, looking from one to another, and announcing that the suites are 'like' or 'unlike'.

From this, A. L. Dryden derived a formula for comparing such data, based on determination of the 'coefficient of correlation', r , as follows:

$$\frac{\Sigma(XY) - nM_xM_y}{\sqrt{(\Sigma(X^2) - nM_x^2)(\Sigma(Y^2) - nM_y^2)}}$$

where Σ is the sign for the summation of that to which it is prefixed, n is the number of pairs of percentages to be used, *i.e.* the number of mineral species, M is the mean of that to which it is prefixed, X is any percentage from one sample, Y is the *corresponding* percentage (*i.e.* of the same mineral species) from another sample under comparison.

But since the value r implies statistical and not geological correlation and since such values cannot be compared with one another as simple percentages (*vide* formula), a 'coefficient of determination' must be used which is arrived at by squaring r . Thus used r^2 is capable of giving in terms of simple percentage an expression of the proportion of elements common to two samples. In an example given comparing two samples A and C, $r = .70$, hence $r^2 = .49$, which is the percentage of elements of A common to C; by subtraction, .51 is the percentage or fraction of elements not common to the two samples.

Arising from this consideration are the following chief points:

- (1) r^2 with heavy minerals is generally large, having a value between .50 and 1.00. If no species are common to two samples (as exemplified) $r^2 = 0$; if some are common to both, r^2 will vary from 0 to a maximum possible value of 1.00 when percentages are identical.
- (2) Varietal features of one species (as often used for heavy mineral correlation) may be treated in the formula as

separate mineral species. They thus increase the number of species used in the formula and affect the reliability of r (hence r^2).

- (3) Reliability of such a statistical method increases with the square root of the number of observations. Thus 16 observations (or mineral species) will give twice the reliability that 4 observations or species will give.
- (4) Closely spaced samples give for r (hence r^2) a large value with small probable error.
- (5) Where statistical formulae, such as the above, are employed, this implies sufficient known related samples so that statistical comparison of unknown may be reliable and valid.

'As the number of samples increases, and as greater and greater information about them is learned in the field, numerical comparison becomes more and more important and wholly supersedes visual inspection in value.'

The present author has purposely given some prominence to A. L. Dryden's original thesis because in cases where frequency estimations depend on actual counting, there is no doubt that unless those counts are properly compared and interpreted, they can prove as ineffective and misleading as purely qualitative methods. Pursued mathematically, in such a way that a rational, statistical interpretation can be placed upon them, then such determinations at once assume a totally different character and deductions may be made, not only by the petrographer but equally by his reader, which will have some sound relationship to actual facts.

Counting minerals grains is only possible where (a) the number of residues is limited, (b) time is not an important factor, and (c) results are not expected on the 'mass-production' principle. Consider for a moment an example in one of many oilfield laboratories known to the author. Here, when at high drilling pressure, as many as 50 to 100 samples may accumulate from a few wells in one day; the field being a youthful one, structural interpretation is awaited impatiently and critical evidence is desired from each of these samples in the shortest possible time. Supposing the 100 samples to average 1,000 mineral grains each, this means counting no less than 100,000 grains. Translate this into daily routine as distinct from research with purely scientific motives spread over a period of time, and the task becomes superhuman; certainly few pairs of eyes could stand the strain long without material damage, modern point counter notwithstanding. The method has actually been tried under the exigencies of oilfield development in more than one instance known to the author, but it had definitely to be abandoned

from the sheer impossibility of the individuals to cope with the mental fatigue involved.

As in most things, a compromise is possible. In those circumstances where time and all other conditions permit and where accuracy is urgent, counting should be adopted and a full statement of the method of preparation of the concentrates and of the limits of accuracy of the counts should be given; further, a statistical basis of comparison should be employed wherever possible. In other less important cases, limit the count to, say, four to six chosen (and representative) fields and average the results. Where one person is continually responsible for the results and for any interpretation which may be placed upon them and where he feels himself sufficiently safe to adhere to the empirical and quicker method of eye-estimation, let him not be afraid to continue in so doing. He may draw some comfort from the fact that in economic work, where these methods are still in vogue in many different countries all over the world, for every grain counted there are probably at least one hundred deemed only worthy of passing inspection.

In the matter of recording frequencies, almost every author seems to have devised his own method and there is still no recognized convention. Broadly speaking, the various records fall into one of three categories: descriptive, graphical and quantitative.

The descriptive method recognizes the use of such terms as 'abundant', 'common', 'scarce', 'rare', or 'ultra-dominant', 'dominant', 'frequent' and so on; qualifying adjectives, e.g. 'very', 'exceedingly', etc., are from time to time added to raise or lessen the status of a mineral by a slight amount in the frequency scale. But the value of 'very' is often debatable, so for that matter is 'exceedingly', certainly in this present context.

The trouble with such terms is that different authors interpret them in different ways; while everyone may read an unequivocal meaning into two antipathetic expressions such as 'rare' and 'abundant' it is certainly not so easy to decipher the intended significance, or the actual fact underlying 'scarce', 'very scarce', 'rare', 'exceedingly rare' applied to a mineral in a range of samples.

In the original volume of this book (1922), the author suggested the use of some of these descriptive terms as in the accompanying table. At a later suggestion of W. W. Watts, each word or symbol was given a number, ranging from 9 downwards, as the mental picture conveyed by comparison of figures rather than of letters of the alphabet is a decided advantage for correlation purposes.

Term	Symbol	Proposed Number
'Flood'	F	9
Very Abundant	A	8
Abundant	a	7
Very Common	C	6
Common	c	5
Scarce	s	4
Very Scarce	S	3
Rare	r	2
Very Rare	R	1

This scheme also embodied the use of the term 'flood', implying the occurrence of a particular species so far in excess of all others as to constitute almost a pure concentrate. P. G. H. Boswell¹ then pointed out that 'The indication of relative abundance by means of numbers seems first to have been introduced by E. Artini², whose scale ran from 1 = very abundant to 10 = very rare. Later F. Salmoiraghi³ reversed the order and used the following scheme: 1 = exceedingly rare; 2 = rare; 3 = very scarce; 4 = scarce; 5 = frequent; 6 = very frequent; 7 = abundant; 8 = very abundant; 9 = dominant; 10 = ultradominant.'

Another method in vogue with some authors is the use of capital letters, small Roman letters and italics to denote extreme abundance, abundance and scarcity, respectively. Applied to complete mineral composition in the 'light' and heavy groups, G. M. Davies once remarked⁴, 'Owing to the small percentage of heavy minerals, however, one of them may be marked as "abundant", though actually scarcer than a "scarce" mineral of the lighter group'. Thus this simple method also has its drawbacks.

	A	B	C	D	E	F	G	H
Garnet	—	— —	— — —	—	— —	— — —	—	— —
Spinel	— —	— — —	—	— — —	— — —	—	— —	— — —
Magnetite	— — —	—	— —	— — —	— —	— — —	— — —	— —

FIG. 69 Graphical Method of Expressing Frequency.
The letters denote localities

In the graphical method, which has not found general favour, relative frequency is represented by horizontal bars, one bar denoting rare, two bars common, three bars abundant (Fig. 69). The result works out as in the accompanying table. It represents but little, if any, advance on the descriptive method⁵.

¹ *Quart. Journ. Geol. Soc.*, **79**, 1923, p. 226.

² *Riv. di Min. and Crist. ital.*, **19**, 1898, p. 33.

³ *Rendic. Ist Lomb. Sci. Litt.*, **40**, 1907, p. 870.

⁴ *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 81.

⁵ E. Neaverson, *Proc. Geol. Assoc.*, **36**, 1925, p. 252.

The quantitative method is simply the expression of frequency results as actual percentages and implies comprehensive counting of the grains in the manner previously described. Such percentages are the only logical mode of expression when counting is carried out. Today it is an almost worldwide convention.

Thus from all these methods of determining and recording frequency, the operator has a wide choice, depending on the class of work in hand and on the degree of accuracy to be achieved. The author's method is to count and express as percentages where special problems and time allow and to use the '9 to 1' convention in other circumstances, *i.e.* in routine work, without worrying too much what each numeral stands for so long as it is understood that '9' implies quantity, '1' rarity, at each end of the scale. Or, in some cases, the record of a mineral may be marked with an asterisk (*) and where, on account of abundance or for some other noteworthy reason, it is deemed necessary to stress it, the asterisk is underlined thus: *. This is useful when time is strictly limited, or where more definite expressions of frequency would avail but little in the work.

(6) *Reciprocal Relationship* between two or more prominent species is not an invariable nor an infallible test of distinction, though some interesting examples can sometimes be worked out. For instance, the relative abundance of red and yellow rutile is quite a constant factor for certain beds in the Northumberland Millstone Grit; other examples are the brown/blue tourmaline ratio; (a), (b) and (c) types of zircon (where (a), (b) and (c) represent distinct developments); the ilmenite-leucocene ratio; P. G. H. Boswell mentioned 'a reciprocal relation in the matter of relative abundance appears to exist between sphene on the one hand and anatase and brookite on the other' in connexion with the Upper Lias sands of the west of England¹.

Again, such a reciprocal factor depends for its definition on actual counting; where there appears some chance of establishing it for a given set of beds, or even for a definite horizon, the attempt should be made, since this factor will tend to be an index of that sediment and will consequently have differentiating value. It will be noted that this information constitutes a special case of frequency determination and therefore requires the same cautious procedure and deduction as are necessary in that connexion.

(7) *Grade-size* of predominant minerals is a matter of very great importance and frequently is of much consequence in the grouping of samples. Methods of arriving at this factor are described in Vol. I, Chapter IV. Both average grade-size of total mineral assemblage and grade-size of one or more predominant species

¹ *Geol. Mag.*, 61, 1924, p. 257.

may be used as indices of samples in which this factor seems likely to afford a basis of identification; although it must be remembered that change of grade, even abrupt, is not in itself evidence of change of horizon or of formation. Rapid and local lateral variation of facies will thus tend to confuse the issue.

It is relevant to mention here that comparison of total sand-grade (Vol. I, Ch. IV, p. 185) through a suite of samples may be useful in their grouping.

In the matter of size of individual grains, this is often a valuable index, especially where one mineral overshadows all others in this respect. Mica is especially liable to occur in grains from two to four times the dimensions of its associated species. A series of topaz grains, of uniform dimensions 0.2 mm.–0.3 mm. in an assemblage of much finer grade, furnishes another example. Garnet, kyanite, sillimanite and occasionally hornblende, may each occur in similar circumstances, as other species. Finally, it is useful to determine percentage of heavy mineral per grade size and compare samples on this basis. The application of logarithmic moments to size frequency distributions in sediments has been described by W. C. Krumbein¹.

(8) *Shape* of minerals enters into comparative diagnosis of samples to a great extent in many problems of correlation. Some residues, *e.g.* from aeolian deposits, are so conspicuously 'rounded' as to render this factor alone decisive in grouping the samples of which this is a characteristic feature, when residues of contrasted 'angularity' are among those investigated. An unconformity involving aeolian beds resting upon aqueous deposits, or vice versa, is an example of this. Where 'subangularity' is the observed feature, shape will probably be of little determinative importance. On the other hand, decided 'angularity' of grain, in appropriate and contrasted shape-association, is of index-value; for instance, ice-borne deposits frequently exhibit this to a marked degree and may thus be individualized.

Shape of mineral grains is always taken into account in correlation, whether it proves of direct or indirect value; some workers even go so far as to estimate percentages of 'rounded', 'subangular' and 'angular' grains of one common species, *e.g.* zircon, if this happens to occur in requisite variety of shape, but in the author's opinion this is seldom likely to supply data commensurate in value with the effort put forward in their acquisition (see Ch. V, p. 418).

(9) *Prominent Features* of detrital minerals, such as constitute *per se* indices of the samples in which they are recognized, often

¹ *Journ. Sed. Pet.*, 6, 1936, p. 35.

occur and prove invaluable in petrographic methods of correlation. In this category we place not only particularly striking minerals, but also *any* special feature of one or more species which is sufficiently notable to be utilized as an index. Examples of this include sponge spicules, shell-fragments, nodular pyrite, bipyramidal quartz, dolomite rhombs, large mica flakes with included iron-ores, prevalence of (010) kyanite flakes (with straight extinction); magnetite octahedra; knee-shaped twins of rutile; *foraminifera* chambers filled with pyrite and so on. Anything, in fact, which is characteristic and persistent, also somewhat uncommon, is of value in a residue and should be utilized accordingly.

(10) *Character of Total Assemblage*. In the hands of the experienced operator, a glance at the heavy mineral assemblage isolated from any particular sample, is sufficient to impress its essential characters almost subconsciously; many of the foregoing details are automatically assimilated in shaping assessment of the whole and in the course of examination of a series of assemblages, certain striking accordances and discordances are noted mainly on cumulative evidence; thus correlation and differentiation proceed, guided to no small extent by successive impressions of assemblages.

This grasp of essentials, to which reference has before been made, is really the basis of both rapid and accurate work; it is unquestionably the reward of experience and careful observation; this 'assemblage sense' should be cultivated by all serious students of the subject.

To illustrate, many workers on British sediments are familiar with and can recognize at a glance, the source of origin of a particularly heavy mineral suite; this is not an extravagant claim. Such characteristic assemblages of minerals obtained from the Inferior Oolite, Lower Greensand, Thanet Sands (Eocene) and Pliocene deposits, are self-evident to those who have investigated these and many other sedimentary rocks from different geological horizons.

It is not easy to put into mere words the significance of the character of an assemblage or the criteria by which that significance may be appreciated and utilized; instinct plays a large part in the technique. But those who take the trouble to master the above data may be sure that their grip on this aspect of the subject will be firm and lasting and that this new knowledge of sedimentary deposits will reveal many unsuspected features tending to individualize particular formations.

DEDUCTIONS FROM RECORDS

From the schedule of information above described, is deduced certain evidence vital to correlation problems, also to the wider

questions of natural history of sediments and kindred palaeogeographical data discussed elsewhere in this volume (Ch. VI). For present purposes, the desiderata are as follows:

- (1) Lateral and vertical persistence of minerals.
- (2) Definition of zones in vertical sequence.
- (3) Areal correlation and differentiation.

(1) The lateral persistence of individual minerals connotes their uniform or sporadic distribution and is an important factor, especially in problems of areal correlation. Such persistence may be expressed in terms of distance from one locality to another, or in the case of a small area where quarries, pits or well-borings yield the evidence, for example, from point to point as dictated by circumstances. It is desirable to construct a persistence diagram for reference in this connexion and further to estimate the percentage of species which is actually persistent throughout; if this percentage is high (say over 60 %) such an estimate may be of great significance. Fig. 70 shows the type of persistence diagram usually employed. In the diagram a suite of minerals is shown in the left-hand column and the letters P, Q, R, S and T may be interpreted as different localities, oil-well horizons, etc. Other published examples of lateral persistence diagrams are to be found in the references below¹.

The vertical range of a mineral or series of minerals tends to demarcate a zone or group of beds in a formation and a vertical range diagram is sometimes useful in recording such distribution. An example of this type of persistence diagram is given by A. Heard and R. Davies in their paper on the minerals of the Old Red Sandstone².

(2) It follows from what has been written that any peculiar properties of minerals isolated from a sedimentary deposit not only individualize the minerals themselves, but extend to that deposit a definite factor of identification. The narrower the limits within which such peculiarities are confined, the greater the possibility of demarcating zones characterized by particular mineral associations or features. As previously explained, differentiation of strata in vertical sequence depends on the narrowing down of these limits, on the separation of one group of beds from another by means of indicative mineral species or assemblages. This naturally follows from a close examination of any series of samples

¹ H. B. Milner, *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 365; C. Raeburn and H. B. Milner, *Alluvial Prospecting* (Murby, London), 1927, pp. 79, 81; H. H. Thomas, *Quart. Journ. Geol. Soc.*, **65**, 1909, p. 240.

² *Quart. Journ. Geol. Soc.*, **80**, 1924, p. 508.

PERSISTENCE DIAGRAM

Localities	P	Q	R	S	T
<i>Minerals.</i>					
Magnetite.					
Ilmenite.					
Garnet.					
Tourmaline.					
Staurolite.					
Epidote.					
Biotite.					
Leucovene					
Zircon.					
Kyanite.					
Anatase.					
Rutile.					
Topaz.					
Andalusite.					
Spinel.					
Sillimanite.					
Titanite.					

FIG. 70.

taken from selected intervals in a given sedimentary sequence, along the lines already laid down.

(3) This phase of the work has been explained. It depends on careful comparison of samples taken from different points over a given area. The main possibility of error here is in minimizing or neglecting the lateral variation natural to the deposit, an error tending to increase with the distance over which the work is prosecuted.

Such lateral variation usually implies lithology, *i.e.* grade-size of rock-particles, but it may also imply slight changes in mineral composition. In comparing a series of samples taken from a formation over a given area, one may confidently anticipate a 'fundamental mineral suite' which will identify the deposit as a whole and serve to establish relationship between them. The great thing to guard against is stretching comparisons too far; it would be foolish to attempt to 'correlate' rocks of presumed similar age occurring in two widely separated regions such as Britain and the South of France, for instance, at least by petrographic methods. Any such attempt or its equivalent would naturally prove abortive of results of any scientific value. On the other hand, the author has often been asked to define the limits of areal correlation; this is again impossible, since it must vary in every area in which the work is undertaken. Only a knowledge of the fundamental geology of the particular terrain in view can act as a guide; but a safe rule is to err on the side of restriction, or if circumstances suggest that investigations over large areas or great distances are warranted, feel out from one locality to the next with the greatest caution, being constantly on the *qui vive* for abnormalities brought about by the overlapping of two distinctly contributed sediments, or by other complex and fundamental conditions of deposition. The student will soon learn what is practicable and what is not and no point would be gained here by any attempt to set a boundary to the work behind which procedure may be straightforward, beyond which it is fraught with difficulties and pitfalls.

SPECIAL CASES IN THE APPLICATION OF PETROGRAPHIC METHODS TO CORRELATION AND DIFFERENTIATION PROBLEMS

There are certain cases where the natural conditions of a sedimentary deposit render it necessary to take special precautions against mistaken interpretation, or where inherent difficulties are raised in the course of investigations. The most important of these will now be dealt with.

Unconformities. P. G. H. Boswell once remarked that 'unconformities are usually emphasized by the changes in mineral composition, and these support palaeontological and field evidence'¹. Generally speaking this is true; but frequently local erosion has been such, that what is theoretically conceived as the plane of unconformity, is in reality a zone of unconformity, *i.e.* an indefinite thickness of sediment, the combined product of contemporaneous erosion and deposition, with a mineralogical composition having affinities with both the older and the younger deposits.

If a series of samples is taken laterally from the points 1, 2, 3, 4 (Fig. 71), the material collected will be from a 'mixed' zone (dotted) and the mineralogical composition may be represented as follows:

Sample 1	ap.	} The small letters are indicative of transitional variations in composition from A to P, B to P, etc.
Sample 2	bp.	
Sample 3	cp.	
Sample 4	dp.	

Accordingly, lateral variation at approximately the same horizon becomes pronounced in these circumstances and where such a structure is hidden (as it may well be in petroliferous territory which is being explored by drilling), a false impression can easily be drawn from discordances between the 'heavy' residues, structural interpretation suffering in consequence.

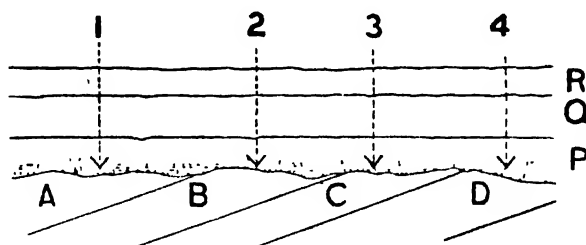


FIG. 71. Heavy Minerals and Unconformities.

The mitigating factor in this case is the tendency for 'flooding' of a particular species to occur wherever different beds are subjacent to P and consequently the four samples may each present this feature and thus furnish a clue to the true state of affairs. The reason for such a tendency to 'flooding' is that the actual process of differential erosion of the tilted edges of A, B, C and D tends to eliminate the less stable and gradually concentrate the more stable minerals in any undulations created; the material then becomes mixed with newly deposited sediment and in this way not

¹ *Geol. Mag.*, 1916, p. 164.

only is the 'mixed' zone initiated, but the proportion of 'heavy' minerals greatly increased, with probable concomitant 'flooding' of one or more species. It is a noteworthy fact that such 'flooding', especially of minerals like zircon, epidote, mica, tourmaline, garnet, rutile, etc., is often characteristic of sediments involved within the zone of unconformity.

Current-bedding. This feature, if developed on a large scale, may prove one of considerable difficulty in using heavy minerals for tracing out horizons. Flooding of the heavier species, much mixing of grades, even of distinctive mineral residues, or the influence of 'gravity sorting' may prevail. If the investigations concern outcropping rocks, some attempt at the resolution of the current-bedding into its components should precede any work on the sediment itself. But where a current-bedded deposit is being drilled and the only evidence available is from well-samples, then the problem becomes an exceedingly complex one, in certain cases impracticable of solution by petrographic methods alone.

Generally, however, it is possible to establish the fundamental mineral suite characteristic of the deposit, irrespective of the amount of disturbance it may reveal and to this extent one current-bedded formation may be differentiated from a subjacent or superincumbent deposit of different age, or from one unaffected by such false bedding. But any attempt to delimit mineral zones within such a formation is likely to be frustrated very soon; none but the broadest distinctions can be drawn in these circumstances.

In the study of current-bedded rocks over wider areas, the difficulty increases with the vagaries of the deposits themselves; lateral variation both of minerals and of grades is characteristic and difficult to follow through, unless the exposures are really good and continuous. Under subsurface conditions, detailed work is practically impossible.

The author's investigations of heavy minerals in certain current bedded formations have revealed the following tendencies which may be helpful in guiding the reader in similar cases; they are not, however, to be regarded as universally applicable to these conditions.

(a) In any set of inclined beds, *i.e.* to the general horizontal stratification, the finest material (grade) occurs at the downward end (bottomset planes) and contains the greatest quantity of heavy mineral (Fig. 72).

(b) The greater the angle of inclination (never more than 41° according to M. J. O. Thoulet), the greater the quantity of heavy mineral at the downward end; flooding of iron-ores characteristic.

(c) In coarse sands the heavy minerals tend to be more evenly

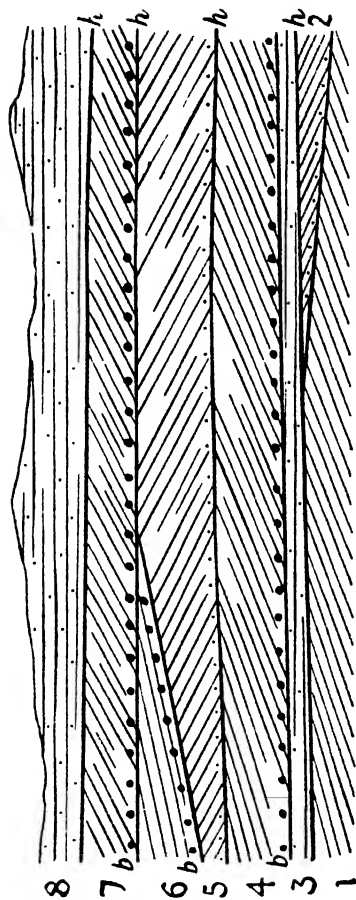


FIG. 72. Heavy Minerals and Current-bedding.

General horizontal stratification represented by planes *h*; bottomset planes containing greatest quantity of heavy mineral. *b*. Beds 1, 4, 6, 7, indicate directions of prevalent current-trend; beds 2, 5, show discordant direction, with less heavy mineral; beds 3, 8, indicate approximately horizontal stratification (undisturbed deposition), with evenly distributed heavy mineral.

distributed throughout the inclined beds, though segregation of the heaviest constituents at the bottomset end is likely to occur.

(d) The largest yield of heavy mineral from current-bedded sands is obtained from steeply inclined beds of local development, *i.e.* where one set of beds occupies a matter of some few yards in actual horizontal distance. Gently inclined beds traceable over several yards on the whole yield less mineral residue.

(e) Beds which lie in a general definite direction, *i.e.* prevalent current, yield the greatest quantity of mineral residue, also the 'basic suite' of the deposit; beds lying discordantly to that prevalent direction tend to be restricted in yield and frequently exhibit mineralogical abnormalities.

(f) Horizontal beds intercalated with inclined beds usually give mineral residues characteristic of the deposit as a whole.

(g) In aeolian deposits current-bedding is liable to be much more confused and irregular in major direction than is the case with water-born deposits; consequently mineral distribution tends to be quite haphazard. Heavy minerals in these circumstances often congregate in pockets, representing lee-side deposition in local dune-formation. In other words, where the beds give evidence of dune characters, as is often the case with aeolian sands, gentle inclinations are planes with least heavy mineral, steeper inclinations, especially towards bottomset ends, being more profitable in this respect.

(h) Both current-bedding and ripple-marking developed in beds of geological age, tend to reproduce the same conditions of natural mineral concentration as encountered in modern shore and aeolian deposits, *i.e.* heavy minerals being naturally segregated from the lighter species.

TRANSGRESSION OF CHRONOLOGIC AND LITHOLOGIC PLANES

The theoretical progression of lithological facies laid down on a continental shelf is from coarse to fine material, grade-size of constituent particles decreasing with depth of water in which they are deposited. This conception normally assumes a static condition on the sea-floor. Frequently, however, contemporary oscillation, gradual upheaval or subsidence of the basin is manifest, with the result that interpretation of the record of sedimentation from the subsequently consolidated deposits is apt to be erroneous if formulated on purely lithological grounds.

Transgression of time-planes, *i.e.* successive phases of sedimentation or bedding planes, by lithological planes, *i.e.* successive

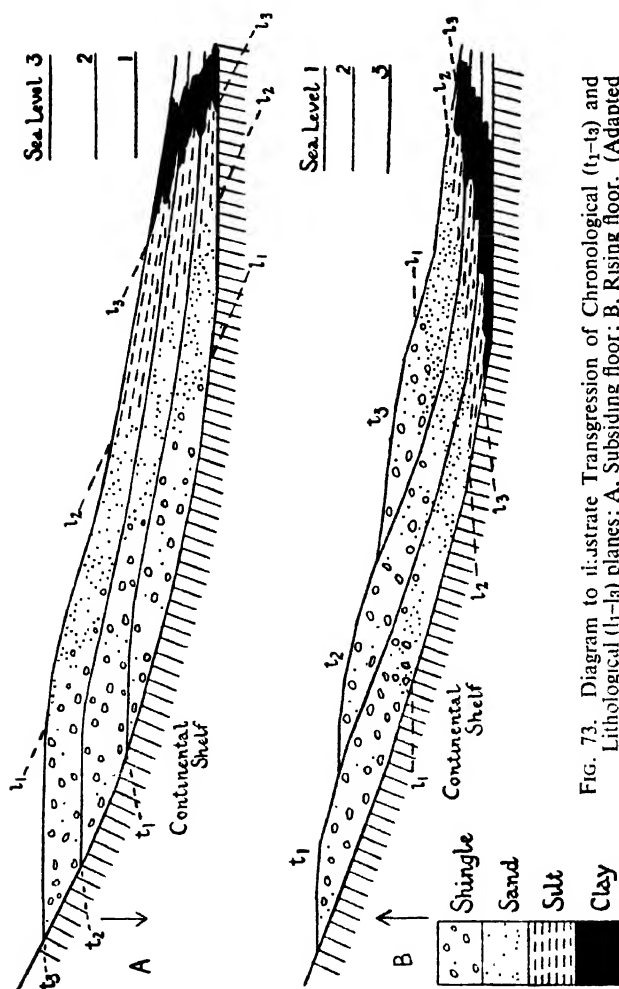


FIG. 73. Diagram to illustrate Transgression of Chronological (t_1-t_3) and Lithological (l_1-l_3) planes: A, Subsiding floor; B, Rising floor. (Adapted by the author from the original drawing by P. G. H. Boswell, *op. cit.*, p. 8)

facies of deposition, is a direct result of one or other of those movements operative during sedimentation and the significance of this phenomenon has been discussed by P. G. H. Boswell¹. In the case of subsidence, vertical thickness of the deposits is accentuated, while in the case of elevation, lateral or seaward spread of the detritus is increased. In both cases definite facies such as sands, silts and clays are in juxtaposition when traced from one time-plane to another, so that ultimately when the deposits are consolidated, the tendency is for them to be differentiated on lithological grounds as true bedding planes, which in this context is obviously fallacious. Fig. 73 makes this clear.

In tracing the mineral assemblage characteristic of the clay facies, for example, variation will tend to occur in the residues as each successive time-plane is traversed, so that lateral correlation of the clay will be a matter of considerable difficulty. If, however, comprehensive sampling of sand and silt grades associated with the clay is carried out, careful observation will detect a mineral suite characteristic of and common to sand, silt and clay components of each successive time-plane and thus a clue is afforded to the real state of affairs. It is essentially the tendency of an inherent mineral assemblage to persist throughout a definite phase of deposition (involving change of lithological facies with progressively deeper water), that makes possible a correct interpretation of the true sequence of events.

A concrete example of this transgression of time and lithologic planes is furnished by the Upper Lias-Lower Inferior Oolite Sands of the West of England. These sands occurring at different localities between the Dorset coast and the Cotteswold Hills have been proved by S. S. Buckman to vary in age from place to place, the time or specific ammonite planes transgressing the lithologic developments. P. G. H. Boswell dealt with this lucidly in the paper cited and with the relevant petrology in a later publication².

Similar complications may be anticipated in any sediments deposited under conditions in which oscillation of the basin has occurred concurrently with deposition and examples are being constantly furnished during the course and geological development of various Tertiary oilfields in Asia and elsewhere³.

Impoverishment of Heavy Minerals. Sedimentary rocks which, from their lithologic character or circumstances of their origin, are deficient in heavy minerals, may present obvious difficulties in the application of these principles. In this category fall reconstituted sediments, very fine clays and most organic deposits.

¹ *Trans. Liverpool Biol. Soc.*, **35**, 1921, p. 5.

² *Geol. Mag.*, **61**, 1924, p. 246.

³ L. D. Stamp, *Journ. Inst. Petrol. Tech.*, **13**, 1927, p. 21.

Where sediments are composed chiefly of '*remanid*' minerals of pre-existing sediments, both quantity and quality of accessory species are liable to suffer. The monotony of a uniform and restricted mineral suite, confined for the most part to such stable minerals as iron-ores, tourmaline, zircon, garnet, etc., persistent through many hundreds of feet of strata, equally prevalent when the same rocks are followed out spacially over large areas, renders subdivision on a petrographic basis very difficult, if not impossible in many cases. None but the broadest distinctions can be made; while comparison of samples from place to place, because of this constancy in composition, can lead only to generalizations, not to define criteria of equivalent horizons. Obviously there is little to be done in such circumstances; where the very indices on which we rely are lacking, other methods must be sought. On the other hand, these cases are, in the author's experience, the exception rather than the rule and even in known reconstituted sediments such as the Wealden of England, differentiation within the formation is possible by means of heavy minerals and areal comparisons can be made with reasonable safety. In this instance it is attention to detail which matters.

With clays, given plenty of raw material to work upon, a reasonable amount of heavy minerals can usually be extracted, except from very pure varieties. The trouble is obviated when dealing with outcropping rocks by collection and treatment of large quantities of material; similarly with shales and other argillaceous types. It is when samples are meagre, as in the case of many oil-well samples, that the difficulty is intensified and the utmost effort has to be made to obtain the maximum quantity of raw material which existing drilling method and modern sampling procedure can provide.

Limestones and similar organic rocks yield heavy minerals in proportion to their impurity; the purest types, *e.g.* chalk, are notoriously sparse in detrital constituents. In such cases recourse must be made to acid solubility or chemical factors as a basis of comparison (Vol. I, Ch. VII), though it is seldom that such rocks are not amenable to treatment by the more precise palaeontological methods. Admittedly chalk is an extreme case; with many limestones it is surprising how much insoluble heavy mineral concentrate can be extracted by efficient methods, especially by centrifuge.

In the matter of saline deposits, including gypsum, etc., research has shown that detrital mineral constituents are in a few cases recoverable and can be used with advantage; also types of mineral crystallization are frequently invaluable in this connexion and should be studied accordingly. Structures revealed from thin sections of these massive mineral deposits are often of definite value as indices of certain developments at particular horizons and are accordingly

admissible as evidence. This aspect of interpretation of thin sections may now be reviewed.

THIN SECTION CORRELATION OF CONSOLIDATED SEDIMENTS

The advent of core-samples of compact rocks in subsurface work long ago enhanced the possibility of differentiating between samples or correlating them by means of a microscopical study of thin sections cut therefrom, more particularly in the case of argillaceous and calcareous rocks. Hitherto, even comminuted limestones have proved, in the absence of other evidence, difficult to study from borehole samples, the usual method being a quantitative comparison of inorganic (detrital and authigenic) material segregated by solution of the organic mass in acid.

In many oilfields, calcareous rocks are a feature of the productive zones; sometimes such rocks are sufficiently individualized and developed to offer no occasion for doubtful recognition from one well to another; on the other hand, where the sequence is made up of alternating limestones with shales, etc., identification and differentiation of successive horizons may be a matter of considerable structural moment, though propounding a problem in specific identification of no mean difficulty. It is here that the thin section, studied from a particular angle, may prove of considerable value.

Investigation of several different limestones, both British and foreign, leads to emphasis of essential morphological differences between types, quite apart from mineralogical and palaeontological variation. For instance, a shelly limestone (so-called) exhibits fragmental remains of the larger fossil shells of all kinds set in a definitely or indefinitely formed matrix, *e.g.* calcareous mud associated with iron compounds, sand, argillaceous matter or even volcanic detritus: at all events a matrix rendered conspicuous by its contrast to the main fossil-fragments and by its particular design, whether uniform or haphazard. Without identifying the fossil remains themselves, or testing microchemically for the type of carbonate composing them, an examination of the relationship of the larger to the finer constituents, *i.e.* the fundamental structure of the rock, may lead to recognition of certain morphological characters common to that rock within a limited lateral and vertical development. With a compact limestone in which no large components are apparent, the nature of the calcite or dolomite mosaic, the degree of crystallization achieved or, alternatively, of mutual interference between the crystals, the manner of dissemination of secondary silica or iron compounds, and so on, may determine individuality whereby a particular example may be recognized. Oolitic, pisolitic and other special types of limestone may

also be investigated from this point of view. Where the organic remains present can be identified, *e.g.* *algal*, *foraminiferal*, *polyzoan*, *bryozoan*, coral and other types, obviously the possibility of linking up similar samples is still further enhanced (Ch. II).

Similarly with shales; often micro-organic (animal or vegetable) structures present may characterize a rock as much by mode of occurrence as by their nature; uniformity of certain diatomaceous shales, relationship of vegetal spores to lamination, etc., are two instances which may be quoted. Quite apart from organic constituents, essential structures of these rocks, *i.e.* degree of parallelism of component elements, development of incipient or obvious slaty cleavage, spherical, elliptical or irregular shape of coarser (usually quartz) elements: all these may bear comparison from sample to sample, from which a measure of identity may be established and correlation rendered possible.

It is not for one moment contended that this line of enquiry *always* leads to precise conclusions or that the method is infallible; but thin section comparison of core-samples, as with outcrop specimens, is now established technique and this particular bias of what is only, after all, intensive study of consolidated rocks according to well-established petrological principles, clearly has merits where no other means of correlating such types are available. It should also be remembered that with argillaceous rocks especially, heavy mineral concentrates of sufficient bulk to make their use practicable in subsurface or for that matter in any other problem of correlation, can only be obtained by treating large quantities of material; and this takes time. Even then, results are not always satisfactory.

The prime essential for this technique is a *really thin section*; this observation may seem somewhat trite, but the author has on more than one occasion been presented with problems whose solution was destined to rest on sections containing quartz of vivid interference colours. Admittedly, certain sedimentary rocks are extremely difficult to cut very thin without losing important constituents or producing holes; since so much depends on mutual relationship of components, holes at least must be reduced to a minimum. There are, however, ways and means of overcoming the 'void' difficulty, as explained in Vol. I, Ch. III. Fortunately skill comes with experience and a good lapidary is seldom mastered, even by a rock-chip measuring less than an eighth of an inch square.

The essential petrology of consolidated rocks is dealt with in this volume (Ch. II) and is the basis of this particular work. As stated above, differentiation and correlation of samples by means of thin sections rely primarily on composition and structure, both of which receive emphasis in that chapter. Given a good knowledge of the

fundamental petrology, it requires relatively little practice to turn one's observations into comparative rather than to the more usual descriptive channels. This work is now a recognized part of the routine of almost every oil-field laboratory known to the author, as it is in all other cases where both surface and bore-hole samples have to be determined to elucidate rock succession and structure.

THE STUDY OF ACCESSORY MINERALS IN IGNEOUS ROCKS

The investigation of isolated accessory minerals and heavy mineral assemblages is by no means limited to sedimentary deposits, as was shown many years ago by R. H. Rastall and W. H. Wilcockson in their work on Lake District granites, later and more exhaustively by A. Brammall and H. F. Harwood in connexion with the Dartmoor granite. This latter research specially inspired many new workers in this profitable field.

Reference has elsewhere been made to methods of segregating accessory minerals from crushed rocks of whatever character (Vol. I, Ch. III, p. 127). Here we have to note rather their significance and application in modern comprehensive studies of plutonic and associated igneous rocks, an application which parallels closely the technique with which this textbook is largely concerned.

In thin section, accessory minerals, save the most prominent and common species such as apatite, zircon and iron-ores, normally escape detection, partly owing to their comparative scarcity with reference to essential rock-forming minerals, partly owing to their small size. Even high magnification, although it may serve to reveal a few different individuals, does not offer the fullest facilities of study and diagnosis of these minerals *in thin section* of the rock as a whole, as it does when loose grains or carefully prepared concentrates are studied according to the principles herein laid down. Further, in the course of geochemical investigations of such accessory minerals, various physical and chemical tests, apart from those determinations ordinarily made with the petrological microscope, are often necessary to their precise diagnosis and understanding and these obviously cannot be accomplished so long as they are components of consolidated rocks.

The pioneer work of A. Brammall and H. F. Harwood on the Dartmoor granite yielded abundant evidence of the value attaching to an intensive study of such accessory minerals. It revealed the existence of a rich and varied collection of species, many of which were previously not known to occur in that rock; it stressed and proved conclusively the significance of varietal characters of these minerals and from this stemmed a direct means of focusing attention on mineral vagaries so often passed by as adventitious

or unimportant. Wider investigations, combining both field and laboratory observations, subsequently demonstrated that particular accessory mineral assemblages may be characteristic of certain 'stages' of intrusion or consolidation or of specific developments and modifications of the normal rock, thus materially aiding correlation or differentiation of types. Their potentiality extends also to geochemical data with which are intimately bound up relevant petrogenetic problems. Thus a new scope of enquiry was instituted, a comprehensive technique established, which both igneous and sedimentary petrographers have long since practised.

Recognition of progress along these lines over the years is attested by the number of papers which have appeared dealing with problems and investigations similar to those defined and solved in connexion with the Dartmoor granite. Among these may be cited the work of M. Chatterjee on the Western Bodmin Moor granite; of P. K. Ghosh on the eastern part of the Bodmin Moor granite; of A. W. Groves on the plutonic rocks of the Channel Islands; of D. R. Grantham on the Shap granite, etc.; of J. G. C. Leech on the St. Austell granite; contributions to our knowledge of certain minerals in Scotch granites by W. Mackie, and researches of F. Smithson on granite and contiguous rocks of Ballycorus district, Dublin¹.

Arising from his work in the Channel Islands, A. W. Groves² claimed that isolated plutonic outcrops which possibly may be derived from the same magma, may be correlated by means of their accessory minerals, particularly in the case of acid rocks. Thus the technique which has been so useful in the study and correlation of sediments has, according to that author, been extended successfully to igneous rock masses. It is, however, only proper to add that this special application to igneous rocks was seriously questioned by A. K. Wells³, who divided the accessory minerals into four groups:

- (a) normal accessories,
- (b) pneumatolytic accessories,
- (c) contamination accessories,
- (d) secondary accessories.

Normal accessories are those developed independently of any special controlling factors such as high flux content, e.g. zircon,

¹ See Bibliography.

² The Heavy Minerals of the Plutonic Rocks of the Channel Islands, *Geol. Mag.*, 64, 1927, pp. 241, 457; also The Heavy Mineral Suites and Correlation of the Granites of Northern Brittany, the Channel Islands and Cotentin, *Geol. Mag.*, 67, 1930, p. 218.

³ The Heavy Mineral Correlation of Intrusive Igneous Rocks, *Geol. Mag.*, 68, 1931, p. 255.

magnetite, ilmenite, sphene, monazite. Pneumatolytic accessories are produced at a late stage in the cooling of the magma, *e.g.* tourmaline, fluorite, topaz, cassiterite, etc. Contamination accessories which infect the magma are those from country rocks, *e.g.* cordierite, andalusite, sillimanite, etc. Secondary accessories are those formed as the result of changes of primary minerals, *e.g.* chlorite, serpentine, epidote.

A. K. Wells considered that only the first group, namely normal accessories, can be considered as potential indices of age and correlation; but this implies reliance on such species as zircon, which is common to granites of all ages. He concluded, 'The correlation of sedimentary rocks by means of their accessory minerals is itself a difficult matter, and the method has obvious limitations. It does, nevertheless, depend upon a simple and comprehensive principle; a certain suite (determined by the rocks undergoing destruction at the time), will characterize a certain distributive province. No such clear and definite principle has yet been established as the basis of correlation of igneous intrusions by their accessories, and the method must remain inconclusive.'

Whatever has been the outcome of conflict of opinion on this matter, it may be safely argued that few investigators of igneous rocks according to strictly modern principles should be content to describe their field-types merely from thin section in future and without regard for their accessory minerals, which must surely receive that degree of attention which their importance unquestionably merits. It is equally clear that detrital minerals, considered primarily as accessory constituents of igneous rocks and thus studied 'at source' are made doubly potent in the solution of problems which seek to harmonize igneous and sedimentary activities at different geological epochs. Only by such thorough investigation of parent-rock and contributed sediment, can the full significance of any particular cycle of sedimentation be grasped.

Finally, probably one of the best links ever established between accessory minerals of *older* parent-igneous rocks and much *younger* sedimentary 'progenies', was by A. W. Groves, in his detection of what Dartmoor Granite contributed to sediments in south-eastern England, a model which, as a directive, has since seldom been equalled¹.

¹ A. W. Groves, The Unroofing of the Dartmoor Granite and Distribution of its Detritus in Southern England, *Quart. Journ. Geol. Soc.*, **87**, 1931, p. 62.

CHAPTER V

SOME EXAMPLES OF DIFFERENTIATION AND CORRELATION OF SEDIMENTS BY PETROGRAPHIC METHODS

Examples of Subsurface Stratigraphical Differentiation and Correlation in the Oilfields of S. California, Texas, Oklahoma, Rumania, Poland—Area (Surface) Correlation illustrated by Cretaceous and Tertiary Rocks of England—Regional work in California—The Correlation of 'Outliers'.

THE principles and practice of 'heavy mineral correlation', as it has come to be known, have been sufficiently discussed in the preceding chapter and are now generally appreciated by workers on clastic sediments. Although conversant with first principles, however, a more detailed exposition of actual examples, carried out on a series of subsurface samples, as under oilfield conditions, and on a series taken from outcropping rocks, will it is hoped be of value to the student; this chapter is accordingly concerned with actual procedures. There is, in point of fact, no material difference in technique in either surface or subsurface studies, excepting as already noted in the methods of treatment of the samples; it is true that with outcropping rocks there is often some field-evidence available as a guide to interpretation and conclusion, which evidence may be and frequently is altogether lacking with well-samples.

It is not an easy matter to give a written account of the petrographic criteria involved in the differentiation of samples, since so much depends on actual microscopical examination of their residues, on comparison of individual and collective properties of the mineral suites as previously described and on what one may term 'intuitive selection', *i.e.* ability to group similar assemblages and to segregate dissimilar assemblages, chiefly a matter of experience. An endeavour is made, however, in the following paragraphs to convey the essential factors in the work by reference to a few of the many cases formerly worked out by different petrographers, including the author, in the hope that these examples and some accompanying photomicrographic illustrations may together afford assistance to those engaged for the first time on work of this

character. The selection of examples has been chosen to cover most possible cases from subsurface stratigraphy to regional and local field-developments.

CASE I. OIL-SAND DIFFERENTIATION¹. A series of core- and bit-samples from producing horizons penetrated by certain wells at depths from 3,500 ft. to 4,800 ft. below the surface on the Santa Fe Springs oilfield, Los Angeles basin, Southern California, U.S.A.

*Casual Grouping*². Into two groups, one characterized by abundant and striking dark green hornblende, the other by epidote, biotite, pyroxene and *no* hornblende.

Detailed Analysis. The initial grouping into two dissimilar lots is confirmed by the following determinations of the essential constituents:

Group 1. Residue plentiful, uniform grade, angular: leucoxene (7)³, green and brown biotite (6), yellow epidote (6), pyroxene and zircon (5), colourless garnet (4), zoisite (3); noteworthy rarity of tourmaline. (Pl. 63A).

Group 2. Residue plentiful, mixed grade, subangular: conspicuous dark green hornblende (8), pale greenish-yellow augite (6), pink garnet (5), green and brown biotite (5), leucoxene (4), epidote and zircon (4), white mica (occasional lepidolite) (3); noteworthy rarity of tourmaline. (Pl. 63B).

Group 1, according to the depths recorded on the slides, characterized a zone between 3,500 ft. and 3,850 ft.; the residues of this group are all very similar and no subdivision is possible. (This is the 'Bell' or upper oil-zone of the field.)

Group 2 characterized a zone below 3,980 ft. down to 4,800 ft. in some samples investigated; the residues in this group are fundamentally similar, but there is a gradual and progressive change in the relative frequency of hornblende and garnet with depth of sample, deeper samples yielding more garnet than the shallower ones. (This is the famous 'Meyer Sand', the main oil-producing horizon of this field.)

Thus the mineral suites characteristic of Groups 1 and 2 respectively are quite different as seen under the microscope, hence samples from the two horizons were easily separated and correlation of each zone from well to well established.

CASE II. OIL-SAND DIFFERENTIATION⁴. A series of core-samples from two wells close together, from producing horizons of the Huntington Beach oilfield, Los Angeles basin, Southern California, U.S.A. The samples are from depths between 2,780 ft. and 4,850 ft.

Casual Grouping. Into two groups, one characterized by a flood of pyrite, with muscovite, tourmaline and garnet; the other by much less pyrite, much zircon and abundant large, angular pink garnets.

¹ Author's analysis.

² This has reference to the first segregations of dissimilar 'slides' resulting from the preliminary 'run-through' (p. 382).

³ Author's expression of frequency (p. 394).

⁴ Author's analysis.

Detailed Analysis. The casual grouping is sustained, but a transitional group between the two main groups is separable as follows:

Group 1. Abundant residue, somewhat angular; composed chiefly of a flood of angular pyrite, often attached to quartz; muscovite (6), prismatic tourmaline (3), irregular, colourless garnet (5) and zircon (3). (*Pl. 63C*).

Group 2. Abundant residue, subangular; diminishing pyrite, other opaque minerals appearing; pyrite (6), prismatic tourmaline (4), pink garnet, ilmenite and zircon (2).

Group 3. Coarse, angular residue, mixed grade; a little pyrite. Pink garnet (8), zircon (6), tourmaline (4), ilmenite and leucosene (4), titanite (3), muscovite (2). (*Pl. 63D*).

Group 1, according to the recorded depths of the samples, characterized a zone between 2,780 ft. and 3,240 ft.; this is known as the 'Bolsa Zone'.

Group 3 characterized a distinctly different and deeper horizon (between 3,500 ft. and 4,850 ft.) known as the 'Ashton Zone'.

Group 2 characterized a transitional zone between the two in which the diminishing pyrite and gradual enrichment of the residue by other species are observed.

Thus the upper 'Bolsa' and lower 'Ashton' zones are clearly differentiated and no difficulty was occasioned in separating samples from both, though the extent of the transitional zone might be hard to determine. The lithological evidence of the samples supported the petrographical analysis, those of the 'Bolsa' being chiefly sandy shale or mudstone, from which a pyritous and somewhat restricted mineral residue would be expected, the samples from the transitional zone being more arenaceous, while those from the deep horizon were mainly coarse sandstones from which a rich mineral suite might reasonably be anticipated.

CASE III. THE COMPREHENSIVE ANALYSIS OF A PRODUCING OIL-SAND¹. The chief diagnostic characteristics of one of the Middle Oligocene producing oil-sands at Goose Creek oilfield, Texas, U.S.A. (Average of three samples.)

The samples were obtained from about 2,200 ft. below surface and were submitted to simultaneous micro-organic and petrographic analysis from which the following results were obtained:

Lithology. Fine, angular sand, somewhat calcareous, with appreciable amount of clay and conspicuous fossil-shell fragments; of the latter, nothing determinate.

*Micropalaeontology*². Species of *Textularidae*, *Globigerinidae*, *Rotaliidae* and *Nummulitidae* present; a good foraminiferal assemblage.

Petrography. The essential minerals include quartz, calcite, pyrite

¹ Author's analysis.

² For precise micropalaeontological data see paper by E. R. Applin, A. E. Ellisor and H. T. Kniker, *Subsurface Stratigraphy of the Coastal Plain of Texas and Louisiana*, *Bull. Amer. Assoc. Pet. Geol.*, 9, 1925, p. 79.

and glauconite. Pyrite was removed (Vol. I, Ch. III, p. 124) and the heavy mineral suite isolated: ample and characteristic residue, subangular grains; ilmenite and leucoxene (7), tourmaline, garnet, zircon and muscovite (5), kyanite (3), topaz (3), magnetite (3), staurolite (2). (*Pl.* 63E).

Thus the nature of the organic assemblage and the characteristic heavy mineral suite rendered this particular oil-sand clearly identifiable wherever met with and on such evidence correlation of samples from this horizon from well to well was rendered possible.

CASE IV. OILFIELD STRATIGRAPHY: PETROGRAPHICAL DIFFERENTIATION OF 'STAGES' AND FORMATIONS. The following example illustrates heavy mineral residue differentiation of recognized palaeontological stages and certain principal subdivisions of the Tertiary sequence of the Rumanian Oilfields (Carpathian Foot-hills). The formations represented are the Pliocene, Miocene and Eocene; the stages represented are the Levantine, Dacian and Macotic (Pliocene) and the Sarmatian (Upper Miocene), all, among others, critical horizons in this geologically complex region¹. The series of samples investigated (with the exception of the Eocene) mainly relate to the rocks of the Campina and Moreni districts.

*Petrographic Analysis*².

Levantine. Abundant and varied mineral suite; angular; mixed grade, 0.1-0.25 mm. Conspicuous feature: abundant angular, colourless garnet.

Assemblage constituted as follows: colourless garnet (8), brownish-green tourmaline (6), yellow staurolite (5), leucoxene (including ilmenite) (5), rutile and zircon (4), muscovite, blue-green hornblende and epidote (3), kyanite (2), enstatite and blue corundum (sapphire) (1). (*Pl.* 64A).

Middle Dacian. Abundant residue, less varied than that of the Levantine; angular; uniform in grade, 0.15-0.2 mm., except for the large brownish-green, prismatic hornblende (0.25-0.3 mm.) the conspicuous feature of the suite.

Assemblage constituted as follows: prismatic brownish-green hornblende (7), small colourless, angular garnet (5), rutile and tourmaline (4), iron-stained leucoxene (5), muscovite and kyanite (3), staurolite (2). (*Pl.* 64B).

Lower Dacian. Abundant residue, somewhat similar to that of the Middle Dacian, but more uniform in grade (0.25-0.3 mm.) and rather more hornblende and garnet relatively to the associated minerals, than in that suite.

Assemblage constituted as follows: dark green hornblende (8),

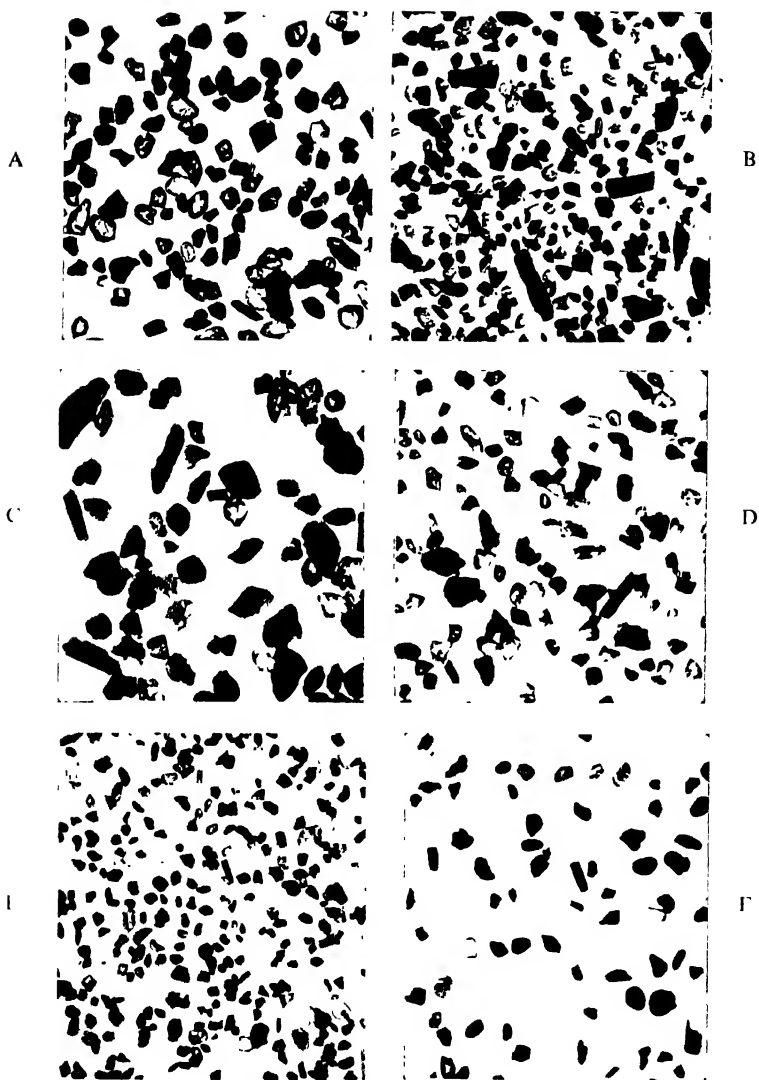
¹ For relevant geological details, reference should be made to two excellent papers, one by G. C. Flower (*Journ. Inst. Petrol. Tech.*, **11**, 1925, p. 61), to whom, among others, the author is specially indebted for many of the samples above described; the other by J. Slomnicki and E. Meyer, *Mining Mag.*, **32**, 1925, p. 265.

² Author's analysis.



A-F. HEAVY MINERAL RESIDUES FROM OIL SANDS IN CALIFORNIA, TEXAS AND ROUMANIA.

- A "Bell Sand", Santa Fe Springs, Calif., U.S.A. [x 25]
- B "Meyer Sand", Santa Fe Springs, Calif., U.S.A. [x 25]
- C "Bolsa Zone", Huntington Beach, Calif., U.S.A. [x 25]
- D "Ashton Zone", Huntington Beach, Calif., U.S.A. [x 25]
- E Oil Sand (Mid. Oligocene) Goose Creek, Texas, U.S.A. [x 25]
- F Oil Sand (Maecotic), Moreni Rourania [x 25]



A-F. HEAVY MINERAL RESIDUES FROM TERTIARY ROCKS, ROUMANIA.

[All x 25.]

A "Eocene"

B "Middle Dacian"

C "Lower Dacian"

D "Maotian"

E "Sarmatian"

F "Middle Eocene"

angular, colourless garnet (3), leucoxene and ilmenite (4), zircon and muscovite (4), tourmaline, rutile and staurolite (3). (*Pl.* 64C).

Maeotic. A distinctive and plentiful mineral suite; angular, very mixed in grade, but tending to be small (average 0.1 mm.).

Assemblage constituted as follows: colourless, small, angular garnet (7), leucoxene (including ilmenite) and green hornblende (5), equi-proportional occurrences of yellow staurolite, brown tourmaline, worn zircon and white mica (4), with accessory rutile (3). (*Pl.* 64D).

Sarmatian. A very rich, uniform, fine grade residue (0.1 mm.), quite different in character from the preceding suites. Conspicuous feature is the variety of mica present.

Assemblage constituted as follows: leucoxene (including ilmenite) (8), garnet (7), muscovite (large flakes, up to 0.35 mm.) (6), green mica (3), greenish-brown biotite (3), tourmaline, epidote, zircon and rutile (5), staurolite (3), glaucophane (2), yellow zircon, hyanite and green hornblende (1). [N.B.—Note impoverishment of hornblende compared with preceding suites.] (*Pl.* 64E).

Middle Eocene (Moldavia). Not quite such a prolific yield of heavy minerals as with the other samples, but the suite is again distinctive, the characteristic features being the abundant rutile and zircon and the mixed grade of the residue.

Assemblage constituted as follows: leucoxene (7), dark brownish-yellow rutile (7), two different types of zircon, large rounded prismatic grains and small fractured grains (together 7), garnet and tourmaline (5), muscovite and staurolite (3), titanite (1). [N.B.—Note absence of kyanite, hornblende and epidote characteristic of some of the above samples and horizons]. (*Pl.* 64F).

Thus, not only were the heavy mineral suites yielded by samples from the Pliocene, Miocene and Eocene formations distinctive and accordingly separable, but in the case of the Pliocene, three of the four recognized stages were differentiated (Pontic material not available for study) and further, in that of the Dacian, the very rich oil-bearing horizon, middle and lower subdivisions were clearly recognizable.

CASE V. STRATIGRAPHICAL IDENTITY OF PRODUCING OIL-SAND¹. Some oil-saturated sands from wells on the Moreni field, Rumania. Determination of the producing horizon. The oil and petroleum residue had to be extracted with chloroform at the outset.

Casual Groupings. All mineral residues similar in this series, no subdivision possible.

Detailed Analysis. The quantity of residue varied somewhat with the samples, but mineralogical composition and physical characters were constant. Suite as follows: leucoxene (including ilmenite) (6), angular colourless garnet (6), zircon (5), yellow staurolite, brown tourmaline and muscovite (4), kyanite (1). (*Pl.* 63F).

The minerals tended to be small in grade, about 0.15 mm., and the residue as a whole compared favourably with that obtained from the Maeotic samples described under Case IV above. It lacked the distinctive

¹ Author's analysis.

greenish-brown hornblende characteristic of the Dacian samples, while its general appearance indicated that it bore no relationship to the rocks of that horizon. Hence the Maeotic horizon of these oil-sands is concluded¹.

CASE VI. FORMATIONS DIFFERENTIATED BY INDEX-MATERIALS. H. R. Lovely and F. P. C. Feilman described an interesting example of petrographic differentiation of two important formations, viz. the Wygoda Sandstone (Eocene) and the Jamna Sandstone (Eocene-Cretaceous) of the oilfield region of Boryslaw, Poland². The distinction between the two formations was based in each case on one mineral species, *kyanite* as typical of the Wygoda Sandstone and *epidote* characteristic of the Jamna Sandstone, but absent in the Wygoda; otherwise samples of the deposits contained ilmenite, tourmaline, zircon, garnet, rutile and staurolite common to both and in some instances the respective mineral suites showed much morphological resemblance.

CASE VII. CORRELATION OF OIL-SANDS BY EXHAUSTIVE INVESTIGATION OF THE PHYSICAL PROPERTIES OF THE COMPONENT MINERALS. A. C. Trowbridge and M. E. Mortimore contributed a paper on the correlation of four well-known producing sands, the Wilcox, Hominy, Bartlesville and Elgin, of N.E. Oklahoma, Mid-Continent Oilfield, U.S.A.³

Their thesis is interesting on account of the stress laid on the physical properties (size and shape) rather than on the nature of the mineral constituents of the sands, also for the methods the authors adopt for recording 'mechanical, shape and mineral analysis results', i.e. by means of graphical representations.

The work is comprehensive and practically amounts to an intensive study of the sediments considered mainly from the lithologic standpoint, though micro-organisms as well as certain accessory heavy minerals are utilized. The graphical representations and charts are supported by photomicrographic illustrations to emphasize the features of dissimilarity between the samples of these sands.

In the case of the four sands and an 'unknown' investigated, the data relied on for differentiation and correlation included fossils, degree of angularity and/or rounding of the constituent grains, shale fragments where present, chlorite, muscovite, magnetite, pyrite and pyrite crystals, quartz in greater quantity than 90%, zircon crystals, angular zircon, rounded zircon, tourmaline crystals,

¹ For relevant geological detail, see paper by J. Slomnicki and E. Meyer, *Mining Mag.*, 32, 1925, p. 269.

² *Journ. Inst. Petrol. Tech.*, 11, 1925, p. 593.

³ *Econ. Geol.*, 20, 1925, p. 409.

angular tourmaline, rounded tourmaline; the results may be summarized as follows:

Wilcox Sand. Grade: well sorted, 55% to 75%, $\frac{1}{4}$ mm.; shape: angular, subangular and fairly well rounded grains in equal proportions; no rock-fragments; minerals: muscovite absent, magnetite rare to common, pyrite rare, rounded tourmaline common, more than 90% quartz; practically unfossiliferous.

Hominy Sand. Grade: fairly well sorted, 40% to 65%, $\frac{1}{4}$ mm.; coarser than the Wilcox. Shape: large well-rounded grains; rock-fragments: green shale; minerals: muscovite absent, magnetite variable, crystallized pyrite common, tourmaline angular and well rounded; fossils: limited but recognizable microfauna.

Bartlesville Sand. Grade: not well sorted; shape: angular grains predominate, small percentage of fairly well rounded grains; no rock-fragments; minerals: muscovite rare or common, magnetite rare, tourmaline and zircon rare in crystals, chlorite present; practically unfossiliferous.

Elgin Sand. Grade: not well sorted; shape: angular grains predominate; no rock-fragments; minerals: zircon and tourmaline common in crystals, angular and subangular grains; unfossiliferous.

Thus it is seen that the identification of accessory heavy minerals was only incidental to the scope of the whole analysis, which depended in the main on the cumulative evidence of mechanical properties; the authors conclude 'it is possible to differentiate these four sands by physical characters alone'; they note, however, 'certain geographic and geologic limitations to the application of the methods . . .' and 'universal application is not claimed'.

The comment may be made that this work stresses the significance of constancy or inconstancy of mineralogical properties, including physical criteria in petrographic work. But relying entirely on physical data necessitates quantitative determinations if the results are to have real correlative value and where time is an essential factor, this may be impracticable; in any case, the limitations are probably narrower than when heavy mineral assemblages are used as the governing elements of differentiation, since physical properties of sediments are prone to much more rapid variation than accessory mineral constituents.

CASE VIII. STRATIGRAPHICAL DIFFERENTIATION (FIELD-OUTCROPS). From time to time the author has in the past published accounts of the value of petrographic methods in the geology of the Weald of S.E. England, where the deposits are for the most part exceedingly variable lithologically and where palaeontological evidence is often meagre or entirely lacking. Work in the East Grinstead district illustrates this application¹. In this case nearly

¹ H. B. Milner, *Proc. Geol. Assoc.*, 34, 1923, p. 283.

200 samples were collected and investigated from outcropping rocks in an area of approximately 36 sq. miles, five different stratigraphical subdivisions being involved and two distinctive lithological developments. The results, for comparative purposes, may be summarized as in the accompanying Table 6 (p. 422).

It will be observed that there are significant differences in the amounts of mineral residue extracted from each member of the Lower Cretaceous series represented.

The *Upper Tunbridge Wells Sand* is essentially a zircon-rutile suite of distinctive character; the *Grinstead Clay* has a restricted muscovite-tourmaline-zircon suite, with absence of secondary pyrite (characteristic of the older *Wadhurst Clay*); the *Lower Tunbridge Wells Sand* yields a richer assemblage than the others and zircon is usually subordinate to tourmaline in quantity; *Wadhurst Clay* is characterized by pyrite, mica, chlorite and zircon, while the *Ashdown Sand* gives a zircon-tourmaline-mica suite of fine, uniform grade, the first-mentioned mineral nearly always predominating.

Thus each subdivision is identifiable by reference to its particular mineral assemblage, taking into account not only the minerals themselves and their varying frequencies, but also the physical characteristics of each typical suite. For further petrographic work of a similar nature (involving Wealden rocks), see references cited below, where also, some of the typical residues are further illustrated¹.

CASE IX. STRATIGRAPHICAL DIFFERENTIATION (FIELD-OUTCROPS). S. W. Wooldridge investigated the Bagshot Sands (Eocene) of Essex² and in the course of the work had occasion to draw attention to the striking lithological similarity between them and the older Oldhaven Sands, separated from each other by 400 ft. to 500 ft. of London Clay. He says: 'Taken in bulk, the mineralogical contents of the two sands are similar. The differences which appear on closer inspection and which are, moreover, definite and significant, are as follows:'

'In the Oldhaven Beds:

- (i) *Kyanite* larger, better-formed and more abundant.
- (ii) *Rutile*, deep red-brown in angular and rounded grains, larger than similar grains in the Essex Bagshot Sands.
- (iii) *Zircon* much less abundant.
- (iv) *Tourmaline*. 'Green and peach-coloured varieties commoner than in the Bagshot Beds. Also 'squat brown prisms which are rare or absent in the latter'.

¹ H. B. Milner, *Proc. Geol. Assoc.*, **34**, 1923, p. 47; **35**, 1924, p. 383; also (with A. J. Bull), **36**, 1925, p. 312.

P. Allen, *Quart. Journ. Geol. Soc.*, **104**, 1948, p. 257.

² *Proc. Geol. Assoc.*, **35**, 1924, p. 359.

- (v) *Staurolite* is more abundant.
- (vi) *Hornblende* characterized by bluish absorption tints suggesting the presence of the glaucophane molecule.
- (vii) *Garnet* fairly common; rare or absent in newer Eocene.
- (viii) Beds are less micaceous but more glauconitic.⁷

Thus there is plenty of evidence available for distinguishing petrographically between the two formations, quite apart from field-data.

CASE X. STRATIGRAPHICAL DIFFERENTIATION IN CALIFORNIA, U.S.A. F. G. Tickel contributed a paper on 'The Correlative Value of the Heavy Minerals', arising from his investigations of some Tertiary formations of part of West Ventura County and the region south of Coalinga, California¹.

He says: 'In the region south of Coalinga . . . the Tejon (Eocene) beds can readily be differentiated, microscopically, from the overlying Miocene formations. The Miocene beds contain abundant minerals of the amphibole group, while the Eocene beds contain almost none'. In the Fernando (Pliocene) of Ventura River, his work led to the detection of two zones, one characterized by glaucophane and green amphibole, the other by epidote. He concludes: 'Study of the heavy minerals constitutes a valuable aid in the correlation of oilfield formations, supplementing and verifying the evidence of the microscopic fossils, or filling the gap where fossils are not found. Mineral grains are not destroyed by the drill; well-samples are just as suitable for study as outcrop samples, and, of course, core-barrel samples offer the best material of all. Much significant information would be obtained by their systematic microscopic study'.

CASE XI. A FURTHER CALIFORNIAN EXAMPLE. R. D. Reed contributed a critical article on the 'Role of Heavy Minerals in the Coalinga Tertiary Formations', wherein he discusses the restrictions, advantages and disadvantages of heavy minerals in correlation². His investigation included typical material from the following horizons: Avenal (Eocene), Kreyenhagen (Oligocene?), Temblor (Miocene), Santa Margarita (Miocene), Etchegoin (Pliocene) and Tulare (Pliocene).

He states: 'Between the Miocene and Pliocene formations of the Coalinga district no persistent differences in heavy mineral content have been discovered. As already suggested, however, any sample of the Avenal sandstone . . . can readily be distinguished by a mere glance at its heavy minerals, from a sample of any of the Miocene or Pliocene formations. There is no reason to doubt that similar differences may be found elsewhere between otherwise similar formations'. 'Finally, there is some reason to believe that heavy mineral zones, at least in the

¹ *Bull. Amer. Assoc. Petrol. Geol.*, 8, 1924, p. 158.

² *Econ. Geol.*, 19, 1924, p. 730.

It cannot be too often stressed, however, that competence in diagnosis of detrital minerals and caution in this particular interpretation of their significance are essentials if successful results are to be achieved; proficiency comes with continuous experience with all sorts and conditions of sediments; but the greater that experience, the more cautious the investigator will inevitably become.

F. Smithson, *Proc. Geol. Assoc.*, **42**, 1931, p. 125.

G. C. McCartney, *Journ. Sed. Pet.*, **1**, 1931, p. 82.

R. Roth, *Journ. Geol.*, **40**, 1932, p. 721.

D. R. Derry, *Journ. Sed. Pet.*, **3**, 1933, p. 113.

D. R. Derry, *Journ. Sed. Pet.*, **4**, 1934, p. 83.

CHAPTER VI

THE BEARING OF SEDIMENTARY PETROGRAPHY ON PALAEO- GEOGRAPHICAL PROBLEMS

The Palaeogeographical Scheme—Mineral Associations (Paragenesis)—Significance of Mineral (Varietal) Characteristics—Minerals as Indicators of Climate—Geochemical Significance of Detrital and Authigenic Minerals—Geochemical Notes on Sedimentary Rock Minerals—Products of Sedimentation Influencing Palaeogeographical Problems.

THE PALAEOGEOGRAPHICAL SCHEME

ALTHOUGH for strictly petrological purposes it may be sufficient simply to effect the qualitative and quantitative examination of a deposit, geologically speaking the investigation is incomplete without carrying the inquiry still further, *viz.*, to a consideration of the source or sources of origin of the material and its bearing on the palaeogeography of the area at the time of deposition. The perusal of this more philosophical aspect of the science is not merely academic; indeed, one might almost say that without such an inquiry all petrographic work must lose both in precision and value: it will certainly lack vitality. As an aid to problems of correlation on the lines discussed in Chapter IV, such research is of fundamental importance.

Tracing the source of constituent particles of a deposit is often by no means a straightforward matter, especially where the locale of a distributive province capable of furnishing the material is obscure or where, owing to widespread erosion, no direct evidence of such a province exists. There may, of course, be more than one individual source. The problems to be faced are, from their very nature, some of the most complex and absorbing that a geologist has to solve; each case must perforce be dealt with on its own merits. Accordingly, we cannot do more here than indicate certain broad factors to be taken into account in all considerations of this character, leaving it to the initiative and ability of the investigator to evolve a more detailed plan destined to lead to reasonable conclusions in the particular case with which he is concerned.

The *Palaeogeographical Scheme* should aim ideally at:

- (a) a rational reconstruction of environment of sedimentation at any given geological epoch, both as regards nature and composition of contributory parent-rocks and sediments derived therefrom;
- (b) a re-establishment of physical conditions under which erosion and deposition proceeded, as may be reflected by mineralogical, mechanical, statistical analyses, etc., of the sedimentary products involved;
- (c) assessment of prevalent climatic conditions during the episode concerned by appeal not only to indicative minerals, but to contained fossil remains (where available) characteristic of the sedimentary products under review;
- (d) delineation of contemporary land/land or land/water configurations;
- (e) consideration of field or other evidence afforded in this research and its bearing on the influence of contemporary or subsequent earth-movements, as may be revealed in present-day disposition of the sediments concerned;
- (f) finally, assembly of all these data, then logical deduction, leading to postulation of geographical circumstances controlling the particular phase of geological history in which the problem was initially set and so attacked.

In short, the initial terms of reference in any *Scheme* of this kind have to be as wide and as comprehensive as are commensurate with the magnitude or narrowness of the problem in hand. The fascination and reward of accurately recapturing these glimpses of ancient geological history are only measurable in the equivalent of successful and ultimately generally accepted theses which serve to advance geological knowledge all the world over.

MINERAL ASSOCIATIONS (PARAGENESIS)

The mineralogical analysis of a sediment will show a certain suite of detrital grains which may or may not be suggestive of the source of origin, either individually or collectively. Generally speaking, there is seldom an instance where the petrographer fails to gain some clue, however small, to the source of some at least of the species represented. In the descriptions of the detrital minerals given in this volume (Chapter I), possible sources of origin of the several species are included to enable an initial estimate to be made; this information, however, only applies to individual grains. Paragenesis is just as important a factor in detrital sediments as in igneous or metamorphic rocks and more often than not indication of the source of origin of the deposits comes from association of species noted rather than from particular minerals.

The association of sillimanite, kyanite, andalusite and garnet or again, a garnet-staurolite-kyanite suite, are both suggestive of derivation from a definite thermo-metamorphic province, just as a titanite, apatite and zircon assemblage (if marked) is indicative of acid or intermediate plutonic rock-types as possible sources of supply. The characteristic association of rhombic and monoclinic pyroxenes, often with ceylonite and possibly a chlorite group mineral in addition, points to derivation from basic or ultrabasic rock-types, while the prevalence of cassiterite, topaz, white mica and rare-earth minerals in certain sands may be equally suggestive of their primary environment. On the other hand, a predominance of the more stable minerals such as zircon, tourmaline, rutile and iron-ores, probably to the total exclusion of such other species as are mentioned above, implies derivation from pre-existing sediments and in such cases location of the ultimate source of origin may be rendered considerably more difficult.

Knowledge of likely mineral associations is also helpful in diagnosis. Paragenetic species not only suggest provenance, but imply certain 'index' minerals anticipatory of related detritals for which the assemblage may be profitably searched. For instance, where diagnosis of a particular mineral proves difficult, and a decision between two or more possibilities has to be made, the claim of the more likely species, deduced from the presence of 'indices', often leads to positive identification. Examples of 'index' minerals and the suites thus implied may be given:

Olivine, magnetite, chromite, picotite, antigorite or chrysotile, ceylonite, rhombic and monoclinic pyroxenes.

Cassiterite, tourmaline, topaz, fluorite, apatite, muscovite, hypersthene. *Corundum*, purple quartz, topaz, garnet, spinel, monazite, titanite, (?) beryl, often with members of the sillimanite suite (below).

Sillimanite, kyanite, andalusite, chiastolite, staurolite, topaz, monazite, tourmaline, garnet, cordierite.

Diopside, rhombic and monoclinic pyroxenes, amphiboles, olivine.

Epidote, chlorite group, zoisite, garnet, vesuvianite.

Axinite, tourmaline, hornblende, biotite, titanite, epidote, pyroxene.

Chloritoid, muscovite, biotite, tourmaline, titanite, garnet and quartz with abnormal interference colours (strain), pyrite, chlorite group minerals, graphite, corundum, spinel, rutile.

The 'index' minerals are *italicized* in the above list, but it is obvious that other species in the suites may individually or collectively assume equal importance. Once a particular mineral association is established and its relationship to a definite source of origin inferred, confirmation of such provenance should be sought by appealing to significant varietal characters of the index-species. This, however, implies detailed knowledge of the parent-rocks themselves, quite apart from the sediments involved.

Investigations of provenance must take into account not only heavy mineral evidence but also that arising from a study of the coarser constituents, *i.e.* boulders, pebbles and rock-fragments of macroscopic size. Many examples of the significance of these components occur throughout the literature; we may cite A. Gilligan's investigations of the pebbles of the Millstone Grit of Yorkshire¹; T. G. Bonney's work on the Bunter Pebble Beds of the Midlands² and the author's study of Wealden deposits of S.E. England, in which conglomerates developed at certain horizons contain pebbles of undoubted Jurassic origin, thus confirming other evidence as to the essentially sedimentary provenance of these rocks³.

SIGNIFICANCE OF MINERAL (VARIETAL) CHARACTERISTICS

In another direction, investigation of the nature of inclusions in minerals, especially in quartz, frequently repays detailed study; this follows along the lines laid down by W. Mackie in the course of his work on various Scottish rocks⁴; it is emphasized by A. Gilligan in his researches on the Millstone Grit referred to above, while significance of varietal features of and inclusions in certain prominent Dartmoor minerals has been discussed by A. Brammall in his masterly contribution to the subject of provenance.⁵ Writing of the typical Dartmoor detrital assemblage, that author summarizes evidence of 'Dartmoor provenance' in terms so lucid as to rank them as first principles of far wider application. He says, 'Individually the species enumerated . . . do no more than suggest the possibility of a Dartmoor provenance, but possibility might be strengthened to probability by coincidences based on (a) relative abundance, (b) varietal features, and (c) nature of inclusions. Whether probability could itself be strengthened to carry conviction would depend on the number of such coincidences. For example—Zoned zircons alone are of little value as evidence of Dartmoor provenance. Their evidential value rises by virtue of inherent features (abundance, size, nature of inclusions, etc.), and of associations: if they are associated with clear zircons subordinate in amount and showing certain peculiarities, their value is enhanced, and this value rises progressively by association with octahedrite, tabular anatase, monazite, brookite, manganiferous garnet, etc., in varietal agreement with known Dartmoor species.

¹ *Quart. Journ. Geol. Soc.*, 75, 1919, p. 253.

² *Quart. Journ. Geol. Soc.*, 56, 1900, p. 287.

³ *Proc. Geol. Assoc.*, 34, 1923, p. 297.

⁴ *Trans. Edinburgh Geol. Soc.*, 7, 1896, p. 148.

⁵ *Proc. Geol. Assoc.*, 39, 1928, p. 27.

Scrutiny of material along these lines implies the need for an exhaustive examination of material. . . .¹

The importance of these observations is realized by all workers on sedimentary deposits to which the Dartmoor Granite and its associated rocks have been laid under contribution, as shown by A. W. Groves in connexion with the distribution of its detritus in S. England². But the example is of universal significance and the principles implied underlie every investigation into the source of origin of sedimentary rocks.

It frequently happens that a particular mineral will, in its form, colour or other specific character, betray its source of origin by strong resemblance to the same species known to occur in older rocks; this is especially the case with younger sediments which have in part been derived from the breaking up of pre-existing detritus. In this way a flood of light may be thrown not only on the direction and mode of transport, but also on physiographical conditions prevalent at the time of deposition. Thus, staurolite occurring in the Bunter Pebble Beds of S.W. England has been traced to the Armorican massif (or its more northerly extension in Triassic times): hence is deduced the prevalent flow of sediment-bearing currents from the south³.

The author's work on the Pliocene deposits of Cornwall showed that staurolite occurring in these has had the same derivation, while the presence of Lower Cretaceous types of kyanite in the most northerly localities has suggested the flow of sediment-bearing rivers from the north-east, *i.e.*, from the region in which in Pliocene times, the main mass of Cretaceous rocks was extant⁴. Again, in view of W. Mackie's researches on the accessory minerals of Scottish granites (in which he proved the occurrence of monazite in 43 out of 52 examples examined⁵), the presence of this species in the Millstone Grit of Yorkshire, joined to other evidence, reinforces the argument in favour of the contention that that deposit had a northerly derivation⁶.

Later work on the source of purple zircon in Scottish sedimentary rocks furnished yet another instance of the significance of a particular variety of a mineral in connexion with problems of their origin⁷. In this case the provenance is the Lewisian Gneiss. By the same indication it has been shown that the Moine Series is older than the Torridonian and that the latter rocks owe their

¹ *Ibid.*, p. 47.

² *Quart. Journ. Geol. Soc.*, **87**, 1931, p. 62.

³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, **58**, 1902, p. 630.

⁴ *Quart. Journ. Geol. Soc.*, **78**, 1922, p. 348.

⁵ In A. Gilligan, *Quart. Journ. Geol. Soc.*, **75**, 1919, p. 271.

⁶ A. Gilligan, *op. cit.*

⁷ W. Mackie, *Trans. Edinburgh Geol. Soc.*, **11**, 1923, p. 200.

origin partly to the Archaean Gneisses and partly to the Moine Schists. In view of the fact that purple zircon is also widespread in many other sedimentary rocks in this country, being met with, for instance, in Eocene deposits as far south as Dorset, Devonshire and Cornwall, P. G. H. Boswell's contribution to the distribution of this variety is both interesting and suggestive¹. In short, once the ultimate geological source is established of a mineral whose specific properties proclaim it an adequate indicator, it becomes *per se*, an invaluable guide, not only in 'placing' the distributive province, but also in reconstruction of the salient events with which the particular sediment or sediments have been concerned.

In working out problems of this nature, therefore, it is advisable firstly to note the possible types of rocks from which each mineral species may have been derived and secondly to investigate the presence (or absence) of such types within a likely region capable of furnishing the material. In this way palaeogeographical questions arise collaterally and the unravelling of the geological record within the limits of the periods represented by both parent-rock and sedimentary deposit constitutes the crux of the whole matter.

Palaeogeographical restoration, to be complete and accurate, necessitates detailed knowledge of regional stratigraphy and also the absence of imperfections in the geological record. The former may be acquired by the geologist as a result of detailed work—in fact its realization is a *sine qua non* to the successful prosecution of all petrographic work. The latter is largely a matter of chance and naturally varies in different districts. Obviously the more faithfully the history of past geological events is chronicled by the rocks, the more complete is the stratigraphical record and solutions to problems of geographical reconstruction are facilitated accordingly. If, in this connexion, we compare south-east with south-west England, it is at once apparent that palaeogeographical investigations in the former, where there are few gaps within the limiting series as developed, are much more straightforward than in the latter region, where no evidence whatever is preserved of the trend of events between late Palaeozoic and early Tertiary times.

Again, the evidence of organic remains (where these are preserved) must obviously play a fundamental part in enquiries of this nature; only where palaeontological investigations are followed hand-in-hand with petrographical analysis, can we expect to gain the fullest knowledge, enabling each step in the process of reconstruction to be made with a reasonable degree of accuracy.

¹ *Miner. Mag.*, 21, 1927, p. 310.

MINERALS AS INDICATORS OF CLIMATE

The bearing of certain detrital minerals on questions concerning climatic conditions prevalent at the epoch of deposition has received a good deal of attention from various observers. Under certain conditions the evidence afforded is convincing, especially in the case of feldspar grains, but frequently it must be admitted that the indications are inconclusive. As early as 1886, J. W. Judd described the freshness of the feldspar grains of the Nile deposits as indicative of mechanical disintegration and desert conditions, *i.e.* tropical heat by day and rapid cooling by radiation at night¹. H. B. Medlicott and W. T. Blanford², of the Indian Geological Survey, have directed attention to differentiation of altered and unaltered feldspar grains, the latter as indicative of mechanical attrition, the former of chemical weathering; in this way feldspar grains present in the Siwalik deposits and also in the Indo-Gangetic alluvium, are ascribed to the breaking down of the parent-rocks by ice and frost, since they are remarkably fresh and unaltered.

W. Mackie's paper, 'Feldspars in Sedimentary Rocks as Indicators of Climate'³, is another instance of detailed research in the differentiation of fresh and altered feldspar grains as criteria of mode of attrition, hence of prevalent climatic conditions. Where alteration is very marked, the inference to be drawn is that moist and humid conditions prevailed, tending to promote chemical decay; where freshness of feldspar is the marked feature, mechanical attrition under arid or glacial conditions is suggested and in such cases a decision must be made between the one or the other by general stratigraphical and lithological evidence; the marked angularity of grain characteristic of glacial deposits, usually contrasts in a striking manner with the strong tendency to rounding exhibited by aeolian detritus.

The conditions attendant on deposition of the Millstone Grit indicate a prevalent monsoon type of climate, by which heavy rains, capable of feeding large rivers, were maintained; hence weathering of the material was preponderantly mechanical, as evinced also by the character of the grains and particularly by the 'exceeding freshness of the feldspars'⁴.

The more detailed study of detrital minerals has shown that not only feldspar, but also minerals like staurolite, andalusite and kyanite may be indirectly indicative of climatic conditions, partly from observations of their degree of alteration and partly from

¹ *Proc. Roy. Soc.*, **39**, 1886, pp. 215, 217.

² *Manual of the Geology of India*, 2nd ed. (Trubner, London), 1893, p. 201.

³ *Trans. Edinburgh Geol. Soc.*, 1898, p. 443.

⁴ A. Gilligan, *op. cit.*

considerations as to their ultimate origin. In the Pliocene deposits of Cornwall the staurolite grains preserve a subangularity entirely consistent with marine transport; their source of origin from the south-west is suggestive of prevalent currents from that direction, thus reflecting present-day conditions. Confirmatory evidence of this is to be found in the location of the Pliocene outlier at St. Agnes on the leeward side of St. Agnes Beacon (N.E.), and by comparison with prevailing climatic conditions of Cornwall today, where heavy rains frequently accompany south-west winds, we may infer, with a reasonable degree of accuracy, somewhat similar conditions operative in early Pliocene times¹.

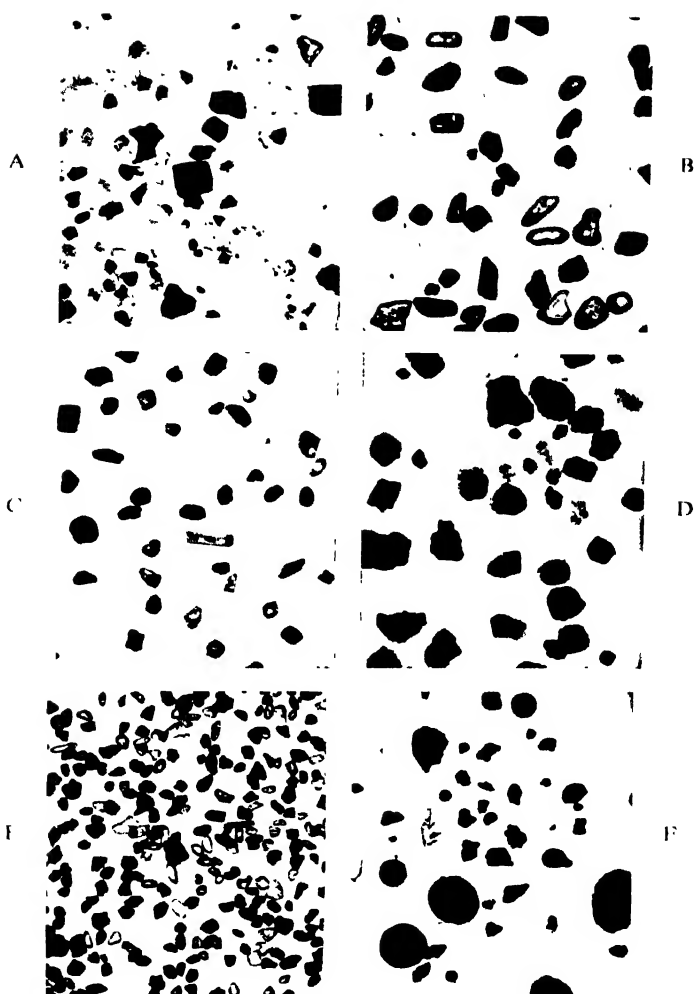
The evidence afforded by andalusite is rather more obscure, but a study of the mineral shows that there are two distinct types of weathering, one characteristic of the species derived from contact metamorphic rocks, the other characteristic of grains derived from andalusite-bearing granites. In the former case the degree of alteration is usually far more advanced than in the latter instance: sericite, kaolinite and possibly chloritic matter may be so prevalent as to cloud the grains entirely, particularly under climatic conditions favourable to intensive chemical weathering. This will apply, of course, to a certain extent to grains derived from granitic rocks under similar conditions, but it is a noteworthy fact that, where this source of the mineral is determined, its freshness and form are clearly indicative of mechanical disintegration, generally under rather frigid climatic conditions.

GEOCHEMICAL SIGNIFICANCE OF DETRITAL AND AUTHIGENIC MINERALS

The investigation of the mineralogical constitution of sedimentary rocks has now proceeded far enough for the geochemical significance of commonly occurring detrital and authigenic species to be appreciated and discussed with a fair degree of accuracy. The cumulative evidence of the study of sediments of all types and geological ages impresses us with certain well-marked tendencies, whereby definite minerals or groups of minerals become criteria of environmental conditions. This does not imply merely a potentiality of these minerals to indicate provenance or peculiar climatic conditions, but rather their role as indices of the varying natural influences, collectively determining the natural history and ultimate geological character of sedimentary formations.

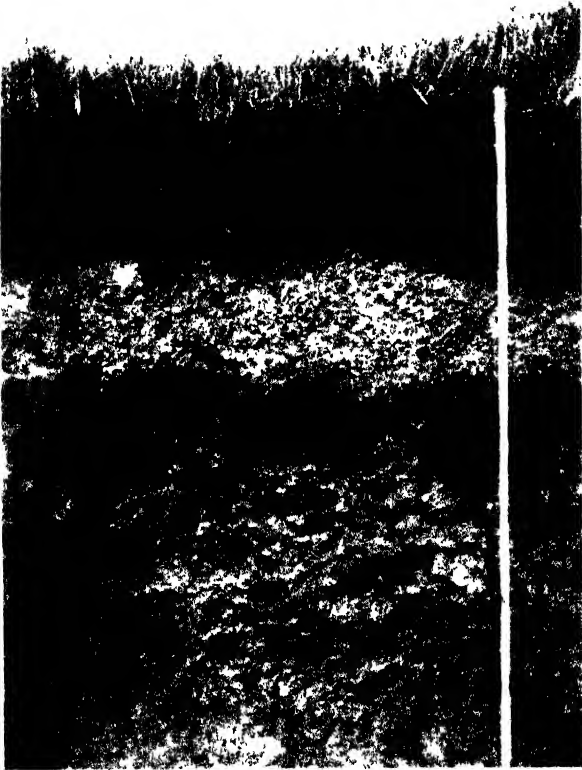
Any special meaning attaching to the presence of some particular mineral or suite of minerals may be directly interpreted from them or may only be suggested when there are other terms of

¹ H. B. Milner, *op. cit.*



A-F HEAVY MINERAL RESIDUES, WEALDEN (LOWER CRETACEOUS), S.E. ENGLAND [All x 25]

- A Weald Clay (Pyrite, Muscovite, Tourmaline, Zircon, Kyanite, etc.), Cullington, Sussex
 B Up Tunbridge Wells Sand (Leucosene, Zircon, Rutil, Tourmaline, etc.), Tunbridge Wells, Kent
 C Lt. Tunbridge Wells Sand (Iron Ore, Leucosene, Tourmaline, Zircon, etc.), Ashurstwood, Sussex
 D Wadhurst Clay (Pyrite, Mica, Quartz with inclusions, etc.), Cullington Wood, E. Sussex
 E Ashdown Sand (Iron Ore, Leucosene, Zircon, Tourmaline, Mica, etc.), Fairlight, Sussex
 F Fairlight Clay (Sphenoidal Siderite, Pyrite, Garnet, etc.), Fairlight, Sussex



A SOIL PROFILE SHOWING SEVERAL HORIZONS

It is a profile of I duna silt loam from Lucas County, Iowa, and is a
planosol formed from loess in Southern Iowa and Northern
Missouri, U S A

(Courtesy R. W. Simonson, Soil Conservation Service, U. S. Dept. Agriculture.)

reference; thus a series of altered microcline grains may be accepted as evidence of a humid environment of sedimentation; or glauconite may in a majority of cases be sufficient proof of a marine environment; but the reason or precise significance of the occurrence of apatite, barite or dolomite in a sediment may not be apparent until full lithological and petrographical data are known.

The presence, as also the absence, of primary rock-forming minerals in sediments *ipso facto* raises questions of relative chemical and physical stability; the survival of certain species under one set of conditions and their destruction under another, are alike provocative of further investigation leading to valuable stratigraphical conclusions; authigenic minerals may not only imply specific geochemical reactions, but they may also directly signify by the nature and achievement of such reactions, environmental conditions; in short, there is a wealth of natural history to be learnt from an intelligent interpretation of sedimentary rock-minerals and it is the purpose of the remaining paragraphs of this chapter briefly to summarize significant data in this connexion. Apart from focusing attention on a theoretical aspect of the petrology of sediments, it is hoped that this contribution will, by creating yet another perspective, serve to stress once more the true aim and scope of all intensive petrographical research.

Preliminary to annotation of most individual minerals and varieties dealt with in this book, it is convenient to summarize in tabular form their general tendencies in sedimentary deposits as regards mode of occurrence, stability and comparative frequency (Table 7).

'Under normal conditions the number of different mineral species occurring in sediments is not great; possibly twenty-five is a fair average for detrital deposits, especially of younger geological age. Older geological deposits (pre-Permian) tend to have a much more restricted composition. . . . Allowing for certain environments where special types of igneous or metamorphic rocks constitute the source of supply of material, the list of possibilities is much larger, though the number of actually occurring species may be comparatively small. Under still more local conditions, for instance, where rarer types of metamorphic rocks or even metalliferous ores contribute material it is obvious that any stable mineral may occur in the derived sediment if initially present in such parent rock-types'¹.

GEOCHEMICAL NOTES ON SEDIMENTARY ROCK MINERALS

The following geochemical notes are intended to be suggestive, not dogmatic:

¹ H. B. Milner, *Mining Mag.*, 1923, p. 80.

Actinolite. Fails to survive prolonged transport; presence usually suggests proximity of parent-rock (metamorphic); incipient alteration to minerals of the chlorite group indicates hydrous environment; to calcite, lime infiltration or influence.

Aegirine. Indicative of alkaline igneous rock province, especially syenite (*e.g.* elaeolite syenite) and frequently associated with feldspathoid minerals (*e.g.* leucite). Tends to alter to analcite. Unstable when detrital and not to be anticipated in sediments of geological age.

Agate. See under *Chalcedony*.

Albite. May be classed as a stress mineral in metamorphic rocks where shearing stress is in evidence, hence to be anticipated in sediments where such material is laid under contribution. As with oligoclase and andesine, is much commoner in sediments than the other members of the plagioclase feldspar group. Albite is not entirely confined to igneous rocks, having been found indigenous to certain marine calcareous muds and dolomites (R. L. Daly, *Proc. Nat. Acad. Sci.*, 3, 1917, p. 659). Liable to alteration in aqueous environment, accentuated in presence of CO₂ or acids, less commonly in contact with alkaline solutions. End products may be sericitic mica and kaolinite or simply kaolinite and quartz.

Allanite (Orthite). Frequently paragenetic with epidote, but liable to alteration to rare-earth carbonates (*e.g.* cerium). Often associated with biotite, in which it occurs as inclusions and thus released on disintegration of that mineral.

Allophane. A product of hydrous alteration closely allied to kaolinite, halloysite, montmorillonite and associated 'clay' minerals. Generally authigenic.

Almandite. Frequently by its form an indication of the intensity of aeolian corrosion, aqueous abrasion, etc. Under certain conditions (? mechanical) it is singularly unstable and is 'lost' in deposits where it might be anticipated to occur in quantity. Chemical alteration in sediments (rarely seen) tends to chloritic matter: some of the isotropic green grains observed in porous sandstones may represent this change; non-survival may be due to chloritization following mechanical disintegration, but further observations are necessary.

Amber. This fossil resin, often containing insect remains entrapped when the material was in a viscous fluid state, is remarkably resistant to weathering, forming on release from parent deposit both large rounded pebbles down to particles of much smaller grain-size. Suggestive of derivation from lignitic coal, fossil wood, of relatively late geological to recent age.

Analcite. Generally a secondary mineral formed in association with other zeolites. It may replace nepheline or sodalite. Zeolitization often proceeds from hydration of feldspar, in this case from soda-bearing plagioclase or orthoclase containing Na. Analcite may be formed by degeneration of soda-bearing ferromagnesian silicates, *e.g.* aegirine. In certain cases it has been proved to be a primary constituent of deep-seated rocks formed under pressure. Its occurrence in sediments must always be a matter of more than usual interest, having regard to its origin and general instability when released from parent rock.

Anatase. Is frequently derived by alteration and leaching of gneiss or schist by traversing hydrothermal solutions. See also under *Ilmenite*.
Andalusite. Degrades with time; may be replaced by kaolinite in 'sealed' environments; alteration to mica denotes hydration and is facilitated by high porosity of sediment. When plentiful a possible indicator of geologically young deposits; universally widespread in Pliocene sediments, especially the most porous arenaceous developments; has been recorded from Old Red Sandstone (W. Mackie). An anti-stress mineral.

Andesine. A member of the plagioclase feldspar group characterizing particularly intermediate igneous rocks, *e.g.* diorite, andesite. Records indicate that it is less common in sediments than either albite or oligoclase.

Andradite. A conspicuous member of the garnet group and probably often overlooked in sediments unless carefully searched. Indicative of derivation from feldspathoid-bearing igneous rocks, *e.g.* nepheline syenite; alternatively, it may suggest contact-altered parent rocks especially if wollastonite is present; more rarely, when found with diopside, augite or rarer forms of pyroxene, it suggests a volcanic provenance.

Anhydrite. Originates in the majority of cases by precipitation from saline solution, one of the earliest products to crystallize out with the process of gradual desiccation of land-locked waters. Commonly associated with rock-salt, gypsum and other sulphates. Is readily changed into gypsum by hydration, but the reverse reaction is also possible and has been observed. It may also form at the expense of limestone. In thick deposits or massive state is inferential of lacustrine, lagoonal or land-locked sea environment. In the presence of excess of organic matter, anhydrite may be reduced and deprived of its sulphur or, put in another way, access of methane to anhydrite (or gypsum) produces calcium carbonate, sulphuretted hydrogen and water; the reaction is probably reversible and this accounts for the diversity of conditions under which anhydrite is found. This mineral should always be studied in its relationship to associated salts and other rock-types.

Ankerite. Affiliates dolomite and siderite and is developed under similar conditions to the former, though implying co-existence of iron-bearing solutions. As an authigenic mineral ankerite is often found in association with coal, but generally its habitat is limestone, in which it is often accompanied by pyrite and sometimes authigenic albite. Acts as cementing medium in Millstone Grit, Anglesey (F. Smithson).

Anorthite. The lime-bearing plagioclase feldspar derived essentially from ultrabasic rocks, less commonly from contact-altered limestone. Anorthite tends to alter rapidly, usually to sericitic mica, kaolinite, one or other of the zeolites, zoisite or calcite and it therefore fails to survive transference to sediments except under exceptionally localized conditions; such alteration is chiefly brought about under hydrous conditions, especially in the case of calcite where percolating waters charged with CO₂ have access.

Anorthoclase. Intermediate between albite and microcline in composition and partaking of the same degeneration characteristics as those

minerals (*q.v.*). Its presence in sediments implies derivation in part from volcanic rocks of an alkaline petrographic province. Frequently associated with sanidine (with which it may be intergrown) which, if found, provides confirmatory evidence of provenance of the sediment involved. Its occurrence in certain Cretaceous Fuller's earths of Britain is significant (see p. 45).

Antigorite. Essentially an alteration product characterizing serpentine rock, developed from such minerals as olivine, enstatite, hornblende, diopside or other magnesian minerals in environments where relaxation of basic and ultrabasic rocks is brought about by hydrous or hydro-thermal conditions. Never a primary species. Persistence in sediments determined by proximity to relevant source of supply: not to be anticipated in deposits of geological age or where long-distance transport is implied.

Apatite. Survives in argillaceous (impervious) rather than arenaceous (porous) rocks, or in 'sealed' sediments, *e.g.* loamy Thanet Sand protected by cover of Chalky Boulder Clay (P. G. H. Boswell); destroyed in lime environments by solvent action of carbonic acid generated by percolating water; present usually in silt, clay, shale or red marl, products of continental, lacustrine, fluvatile, rarely brackish marine environments. Degenerates under marine conditions forming secondary phosphates aided by organic selection (see *Glauconite*). Has been noted in Old Red Sandstone (P. G. H. Boswell).

Aragonite. Given the presence of magnesium sulphate in solution and a temperature exceeding 29°C., any carbonate which may be precipitated will be aragonite, not calcite. In this way much of the aragonite is formed which occurs in association with limestone and saline deposits, though another source is the shells of certain organisms (p. 247). Aragonite indicates, *ceteris paribus*, climatic control and a warm sea. The presence of sodium or ammonium carbonate in sea-water favours its precipitation; under conditions in which organic decay is prevalent, the ammonium compounds would tend to be formed, especially in warm environments, thus aiding the deposition of aragonite. This mineral changes easily to calcite, but the reverse process has not been observed authoritatively.

Arfvedsonite. Identification in sediments of this amphibole implies derivation from soda-bearing igneous rocks, *e.g.* nepheline syenite and related pegmatites. It is not, when released, particularly stable, however, and may be wholly or partially replaced by siderite or limonite.

Arsenopyrite. Moderately stable on release from parent mineral veins, sulphide ores, less commonly limestones and schists. Shows little tendency to alteration by weathering, but Scorodite ($\text{FeAsO}_4 \cdot 2\text{H}_2\text{O}$) may represent an end destabilization product.

Astrophyllite. Very rare, unstable and to be anticipated only in localized deposits not far removed from soda-bearing parent granites and syenites.

Augite. If in quantity and fresh, indicates either proximity to parent-rock or preservation in anhydrous environment; degenerates with time, hence met with normally in youthful deposits. An anti-stress mineral.

Autunite. In itself a secondary alteration product of *Uraninite* (*q.v.*) or

other uranium-bearing minerals and implies primary derivation from granite or pegmatite or 'pitchblende' lodes. Further alteration may tend to *Phosphuranylite*, a hydrated phosphate of calcium and uranium of doubtful formula (Dana).

Axinite. Beyond suggestive of pneumatolytic provenance, usually the product of contact-alteration of basic (lime-bearing) igneous rocks, this mineral is of no special significance.

Baddelyite. Mostly detrital in gem gravels, possibly derived originally from syenitic or pyroxene-rich rocks. Very rare, localized and generally unaltered as found.

Barite. Normally authigenic, but may be locally derived; cementing medium of porous, arenaceous rocks, suggesting percolating carbonate- and sulphate-charged waters; or reaction between bicarbonate (infiltrating) solution and pyrite under oxidizing conditions; initially liberated (as barium oxide?) by decomposition of barium-bearing feldspar and mica, especially by subaerial weathering of acid igneous rocks and as an authigenic mineral tends to characterize continental (arid) or lacustrine deposits. In marine sediments (rare) may be segregated by organisms (*rhizopods*): see J. Samoilov, *Miner. Mag.*, **18**, 1917, p. 87.

Barkevicite. Essentially a basic variety of arfvedsonite (*q.v.*) rich in ferrous iron and alkalis and implying contribution to deposit in which it is found of alkaline igneous rocks, *e.g.* nepheline syenite and associated pegmatite.

Basaltine. This mineral implies oxidation of the iron in ordinary hornblende. 'This change occurs in nature when common hornblende is heated to about 800° under oxidizing conditions, as in certain lava flows' (A. N. Winchell). Basaltine in sediments generally indicates contribution from basic volcanic rocks such as basalt and basaltic lavas.

Bastite. Essentially a secondary product (coarse form of antigorite) (*q.v.*) always pseudomorphous after rhombic or monoclinic pyroxene. Formed in hydrous or hydrothermal environments and persistent in sediments whose parent-rocks (usually serpentine) are close at hand.

Beidellite. This mineral with nontronite (*q.v.*) forms an isomorphous series. It tends to occur in 'the finest colloid fractions of clays which are dominantly composed of other clay minerals' (R. E. Grim and R. H. Bray, *Journ. Amer. Cer. Soc.*, **19**, 1936, p. 311). Essentially a constituent of recent clays and soils and often associated with kaolinite (*q.v.*) montmorillonite (*q.v.*) and halloysite (*q.v.*). Possesses a high base exchange capacity. Both feldspar and ferromagnesian minerals may alter readily to beidellite under suitable conditions, *e.g.* by action of solfataric solutions. Decomposition of zeolites is another mode of origin.

Benitoite. A very rare vein-mineral formed in glaucophane schist and similar rocks and only to be anticipated in sediments suitably derived.

Beryl. Parent-rock usually drusy granite or pegmatite, less commonly mica schist. Mostly found detrital in alluvial deposits. Tendency to alter to kaolinite or mica, especially along flaws and fissures in the mineral.

Biotite. If in quantity and fresh, often implies occurrence in 'sealed'

deposit, especially lenticular sandstone in clay or shale; in porous deposit rapidly hydrated; this change may be suggested by presence of minute but perfect zircon crystals (thus released), providing contrast in type with the zircon characteristic of the deposit. Brown variety more stable than the green in sediments.

Boehemite. Most commonly associated with and a principal constituent of *Bauxite*. Can be formed as a result of partial dehydration of *Gibbsite*; in Co. Antrim this reaction was brought about by heat due to lava flows.

Bronzite. A variety of enstatite (*q.v.*).

Brookite. Frequently derives from hydrothermal alteration of gneiss and schist. See also under *Ilmenite*.

Bytownite. This is the rarest member of the plagioclase feldspar group, found in basic plutonic and volcanic rocks. It is still rarer in sediments and easily undergoes alteration on release from parent rock.

Calcite. Seldom detrital in sediments of geological age; a highly stable product of the 'lime environment'; derived from percolating lime-bearing solutions or from organic sources; suggestive of aqueous rather than terrestrial environment, though may be formed under fluvial and lacustrine conditions. Too ubiquitous to be indicative of very precise environments.

Carpholite. A rare manganese mineral derived from quartz and metalliferous veins. Has also been found as a superficial, fibrous deposit on granite.

Cassiterite. Locally significant of distributive province; durable except under hydrothermal conditions (impregnation of porous sediment by thermal waters). Has been recorded from Triassic deposits (P. G. H. Boswell).

Celestite. When in association with other saline deposits, *e.g.* anhydrite, gypsum, rock-salt, also with limestone, the presence of this sulphate points to much the same environmental conditions as do those deposits. It can be formed directly from sea-water with or without the action of organisms. In association with freshwater marls, etc., it implies direct precipitation from those waters, the ultimate source of the strontium being igneous rocks. The presence of this mineral is to be anticipated in the above-mentioned rocks, but it appears to be sporadically developed and not in itself significant of any peculiar conditions beyond those noted.

Ceylonite. Of no special stratigraphical significance; may be anticipated where corundum, andalusite, sillimanite and kyanite are *all* present; under some conditions its absence may be due to alteration to steatite.

Chalcedony. Seldom detrital; more commonly the cryptocrystalline product of secondary silicification by infiltration of aqueous solution; often of debatable origin and significance in sediments. The same applies to varieties, *e.g.* agate, jasper etc. (p.74) when identified in sediments.

Chalcopyrite. A widespread copper mineral often derived from hydrothermal vein deposits. Tends to weather to sulphate.

Chamosite. An alumino-silicate of iron occurring particularly in sedimentary iron ores. It readily alters by oxidation to a mixture of

Kaolinite and Goethite. It is relatively unstable and therefore not to be anticipated in detrital sediments other than in an iron-ore environment. **Chert.** In a majority of cases indicative of marine origin of the deposit in which it is found; generally of organic derivation, *e.g.* *radiolaria*, sponge spicules. More rarely it may occur as a siliceous replacement of original calcium carbonate in the form of fossil shells, or as representing deposition of colloidal silica in calcareous ooze while the latter is accumulating on the sea-floor. Where chert is common in a detrital sediment, contribution from (usually) shallow water limestones is suggested.

Chiastolite. Like andalusite, of which it is a variety, an anti-stress mineral, but probably less stable chemically and physically than that species; unlikely to survive redeposition; under conditions of hydration, prone to alteration to mica, presumably with separation of carbonaceous matter; to be anticipated locally in semi-porous, fine-grained sediments. **Chlorite.** See 'Chloritic Matter'.

'**Chloritic Matter**'. Prevalent chloritic matter in sediments is suggestive of original occurrence of ferromagnesian minerals, *e.g.* augite, hornblende, biotite, etc. It is doubtful whether any precise member of the chlorite family is commonly identifiable as a detrital mineral, owing to possible wide variation in composition. Chloritization has probably proceeded in most cases before the original species reaches the sediment; incipient alteration noted in detrital augite, hornblende, biotite, tourmaline (?) suggests, however, contemporary change. Chloritic products chiefly noted in 'open', coarse sediments to which meteoric waters have easy access; they are far less common in 'sealed' deposits.

Chloritoid. In so far as sediments are concerned, ottrelite seems to be far less stable than chloritoid, but primarily little seems to be known of the real composition and genesis of these minerals. Some of the Brittany chloritoid is suggestive of development *in situ*; in other cases it is clearly derived. As a local stress mineral, its occurrence in sediments is hardly suggestive of more than provenance.

Chromite. Tends to localize the source of the sediment in which it is found, but has little if any other stratigraphical value.

Chrysoberyl. Parent rocks normally granite-pegmatite or aplite. Generally found as detrital in gem-bearing alluvials (*e.g.* Ceylon). Stable and suffers only superficial tarnish on weathering, unless fractured.

Chrysotile. Dimorphous with antigorite (*q.v.*), with which it is often associated; implies derivation from ultrabasic rocks, *e.g.* serpentine rock. Formed as a result of hydrous alteration of magnesium-rich minerals, or more rarely as a product of dedolomitization following metamorphism of siliceous dolomite.

Cinnabar. A product of solfataric action in hot spring environments, especially near recent volcanic rocks. Deposited from alkaline solution. Rarely found detrital far from source owing to its extreme softness.

Clinochlore. A prominent member of the chlorite group, but not as abundant in sediments as penninite. Invariably of secondary origin, generally after ferromagnesian minerals. May indicate contribution from volcanic rocks which have been subjected to hydrothermal alteration, or from schist or phyllite.

Clinozoisite. Essentially a secondary product of alteration of ferro-magnesian minerals or of lime-soda plagioclase feldspar; or may indicate derivation from metamorphosed, impure limestones in contact zones with basic igneous rocks. Commoner than zoisite (*q.v.*).

Collophane. Occurs both authigenic and detrital in sediments, implying phosphate deposits or derivation from same. 'Considering its softness and comparatively easy solubility, it is not to be supposed that collophane in appreciable quantity could survive either transportation over a long distance or weathering through a long period of time... it may occur rather abundantly as a detrital mineral where source beds are near at hand and weathering has not been too thorough'. (J. H. C. Martens, *Amer. Mineral.*, 17, 1932, p. 153.)

Columbite. Derived from granite and granite-pegmatite, metalliferous lodes. Frequently detrital in alluvial deposits in suitable environments (*c.g.* Nigeria). Stable and persistent, weathering with difficulty. See also *Tantalite*.

Cordierite. An unstable mineral, especially in sediments; in a hydrous alkaline environment it changes to micaceous pseudomorphs such as pinite; it may be produced in sandstone by 'vitrification' due to contact with igneous rock-magma (H. Bücking, quoted by F. W. Clarke, *Data of Geochemistry*, 1924, p. 410). It tends to be preserved in impervious deposits not far removed from source of origin. Has been recorded from Carboniferous and Triassic deposits (P. G. H. Boswell).

Corundum. Although primarily a stable species, prolonged action of percolating water may produce alteration products, *e.g.* diaspore; dissolved salts in such waters may, by coincident action, produce various compounds, *e.g.* muscovite, chloritoid, zoisite, etc. It is suspected that such changes are capable of taking place in porous sedimentary environments, but to what extent is unknown; this may account for the increasing rarity of corundum in deposits of geological age. It tends to be commoner in marine than in other types of sediment: a saline environment may retard alteration, hence its preservation, but further observations on detrital occurrences are required.

Crossite. A rare and localized amphibole associated with schists and contact altered rocks of which, in sediments, it is accordingly indicative.

Cymatolite. A name given to an intimate admixture of albite and muscovite resulting from decomposition of spodumene (*q.v.*) which has been influenced by soda-bearing solutions and reactions due to potassium salts. Not a specific mineral and only to be anticipated where spodumene is diagnosed.

Delessite. A ferriferous form of penninite (*q.v.*).

Diallage. A variety of augite or diopside characterized by prominent orthopinacoidal parting, giving the mineral a lamellar or fibrous habit; particularly characteristic of gabbros, to which source, when found in sediments, it is usually traceable. Not to be anticipated in deposits of geological age or far removed from parent rocks.

Diamond. Rare in sediments of geological age; essentially a localized river-gravel mineral of ultrabasic igneous rock origin; less commonly from pegmatite veins and quartzose conglomerates.

Diaspore. Frequently an alteration product of corundum² in aqueous

environment. Also commonly occurs in bauxite deposits. In association with hydrous sulphates implies derivation from volcanic rocks. May also be produced by decomposition of sodalite.

Dickite. Hydrated aluminous silicate, closely allied with kaolinite, but of rarer occurrence, chiefly associated with ore deposits. Also characteristic in certain types of clay.

Diopside. In sediments is prone to alteration to minerals of the chlorite group, calcite, etc., though in 'sealed' deposits, fresh grains may be preserved; probably would not survive prolonged transport or re-deposition.

Dolomite. In detrital sediments almost invariably authigenic and characteristic of, but not confined to shallow water marine deposits; where dolomite is common and calcite rare, organic origin in a 'magnesian sea' may be suggested; alternatively precipitation from percolating waters in continental deposits is possible, *e.g.* where a magnesian limestone is laid under contribution; in this connexion it is noted that Palaeozoic limestones tend to be more highly magnesian than those of younger geological age; thus an abundance of dolomite in a detrital sediment may presuppose the existence of Palaeozoic limestone as a source of the magnesian carbonate. Absence of the lime carbonate would seem to indicate subsequent leaching action, facilitated by access of meteoric water through porous deposit; close textured or impervious rock, *e.g.* marl, silt, favours presence of both calcite and dolomite and this is frequently observed. Dolomitic limestone overlying porous detrital deposits may similarly contribute to the formation of the mineral in those sediments.

Dumortierite. Frequently significant of pegmatitic parent-rocks; also to be expected in association with kyanite, sillimanite, andalusite, etc.

Enigmatite. A rare species derived from soda-rich syenites and trachytes.

Enstatite. Not a mineral to survive much mechanical or chemical stress; by hydration it alters to steatite and minerals of the chlorite group, the former and often the latter tending to be lost in the process of sedimentation.

Epidote. Both detrital and the product of a destabilizing environment; in the latter case derived from ferromagnesian minerals, sometimes garnet and invariably associated with chloritic matter; detrital epidote is frequently unaccompanied by chloritic minerals; the authigenic variety is consistent with continental and lacustrine deposition, detrital epidote being more frequent in marine deposits. Has been recorded from Longmyndian (Pre-Cambrian) deposits (P. G. H. Boswell).

Eschynite. A very rare and local species derived principally from nepheline syenite and only to be anticipated in suitable environments near to parent rock, where it may occur as detrital.

Euclase. A rare beryllium species derived from chlorite schist and associated crystalline metamorphic rocks. Described mainly from localized alluvial deposits (*e.g.* British Guiana). Stable, persistent where found and seldom altered.

Eudialite. Indicates alkaline igneous rock origin, *e.g.* nepheline syenite. Very rare and seldom found detrital except near to source.

Fayalite. Not common in sediments, but may occur locally where acid volcanic rocks are laid under contribution. In recent and contemporary deposits, alluvium, dust, etc., not infrequently derived from disintegration of furnace slag.

Flint. Particles observed in detrital sediments imply derivation either directly from chalk deposits or indirectly through the medium of later-aged sediments or disintegration of gravel. Flint reacts easily to its environment and weathers accordingly. In large fragments or pebbles, much may be learned of the probable history of any particular occurrence from a close study of patination, shape, indentations, variation from surface to centre, proportion of granular chalcedony to opaline silica, presence of organic structures, *e.g.* sponge spicules.

Fluorite. Undergoes alteration in a sedimentary environment invaded by percolating water charged with bicarbonate or alkaline carbonate; sometimes authigenic, cementing sandstone (W. Mackie), or may be formed by replacement of lime carbonate by percolating fluoride solutions in porous sediments; may be significant of fluvial or terrestrial deposits, but this is not invariable. Generally indicative of highly mineralized provinces, often (in Britain) of particular developments of Carboniferous Limestone. Colour may, in conjunction with other varietal features, be suggestive of provenance.

Fuchsite. An uncommon species in sediments and significant generally of micaceous rock derivation. Essentially the product of a quartzite or schist province.

Gadolinite. From pegmatite veins and occasionally found in rare earth deposits as detrital. It is not particularly stable and tends on release to alter to an amorphous state with separation of Cerium and other rare earth oxides.

Galena. May impregnate porous sandstones, *e.g.* Keuper Waterstones, Cheshire, otherwise mainly of alluvial derivation in proximity to sulphide deposits.

Gastaldite. A closely related species to glaucophane having much the same environmental significance and alteration tendencies.

Gibbsite. Origin often traceable to corundum, from which it is formed by action and contact of saline percolating water. Frequently associated with bauxite deposits; may also be directly derived from decomposition of feldspar.

Glaucinite. Where organic structure is evident, marine origin of its environment is seldom in doubt; derived glauconite, however, does occur, usually partially limonitized and lacking organic character (*e.g.* Wealden deposits); frequently significant of stratigraphical breaks, *e.g.* glauconite and phosphate development coincident with subaqueous unconformity between *Dictyonema* shale and glauconite shale, Lower Ordovician, Scandinavia (W. G. Fearnside, *Geol. Mag.*, 1907, pp. 257, 295); also similar association at junction between Chattanooga shale and overlying Carboniferous, Tennessee, U.S.A. (C. W. Hayes, *U.S. Geol. Surv.*, 16th Ann. Rep., 1895, p. 611; 17th Ann. Rep., 1896, p. 523); '... the more significant breaks in a stratigraphic series are likely to be marked by the occurrence of autochthonous glauconite, in many instances associated with, directly above the break or rarely more than a

foot or two above it' (M. I. Goldman, *U.S. Geol. Surv., Prof. Pap.* 129, 1921, p. 1; also 'Association of Glauconite with Unconformities', *Bull. Geol. Soc. Amer.*, 32, 1921, p. 25; also *Science*, 56, 1922, p. 171). Where glauconite and phosphate occur, the latter predominates in littoral facies, glauconite in off-shore shallow water facies, *i.e.* continental shelf (F. Andersson, *Bull. Inst. Univ. Upsala*, 2, 1895, p. 133). Colour may be significant, depth of colour varying inversely with geological age: darkest green in Cretaceous and Tertiary beds, lighter green in Palaeozoic, *e.g.* Cambrian; survival of 'ancient' glauconite mostly due to presence of impervious cover-rock. Both fresh and limonitized glauconite may be present in arable soil, owing its formation to adsorption of potassium compounds in this environment, the adsorptive media being soluble (colloidal) silica and colloidal ferric hydroxide. (L. Cayeux, *Ann. Soc. Géol. du Nord*, 34, 1905, p. 146.) The possibility of some soil-glauconite being derived by circulating waters is to be noted. Gravity may be significant: higher gravity may indicate slightly limonitized glauconite of inorganic origin, therefore not necessarily in marine deposits; lighter gravity is more typical of 'foraminiferal' glauconite, not so prone to alteration (gravity range 2.25 to 2.92). A species of great stratigraphical value in all circumstances (cf. A. F. Hallimond, *Miner. Mag.*, 19, 1922, p. 330). For other references see Chapters I and III.

Glaucofanite. A stress mineral of sporadic occurrence in sediments; may possibly be authigenic (decomposition product), especially if fresh (B. Koto, *Journ. Coll. Sci., Tokyo*, 1, 1887, p. 85). When detrital, often shows chloritic alteration; degenerates with geological age, being observed mostly in middle Tertiary to Recent deposits, especially Miocene marls and silts of widely separated countries.

Goethite. Contains 89.9% of Fe_2O_3 and is a common ferric hydrate derived from decomposition of rocks, precipitation from solution, being both by chemical and organic agency. Seldom of special significance in detrital sediments, unless interpreted in terms of other criteria, *e.g.* stratigraphical evidence, mode of occurrence of containing deposit, etc. Recent X-ray work on altered *pyrite* shows that *goethite* is the normal end-product; thus *pyrite* may be a source of this mineral in sediments (F. Smithson, *Miner. Mag.*, 31, 1956, p. 314).

Gold. Provenance varied, but parent rocks may be quartz veins associated with igneous and metamorphic rocks or quartzose conglomerate (banket); also occurs in consolidated and unconsolidated placer deposits, as nuggets and grains. Extremely stable and resistant to weathering.

Graphite. Much of the so-called graphite in sediments (usually recent or alluvial) is probably amorphous carbon derived by mechanical disintegration from minerals containing carbon inclusions, or else from hydrocarbon impregnation; otherwise of little geological significance.

Grossularite. Generally significant of derivation from contact metamorphosed crystalline limestone confirmed by presence of idocrase or wollastonite; more rarely may pseudomorph vesuvianite or gehlenite (melilite group). Not as stable when released as almandite and liable to alter partially to epidote, chloritic minerals or calcite.

Gypsum. Varied genesis; a favourable environment is that under

which pyrite by oxidation can react with calcareous rocks; it may be fundamentally of marine origin, *i.e.* concentration of saline waters by desiccation; deposition from infiltrating freshwater solutions containing lime-salts will determine its appearance in many porous deposits; often of considerable stratigraphical significance. (See also *Anhydrite*.)

Halloysite. An amorphous constituent of certain residuary clays and significant of probable association with species such as beidellite, montmorillonite. But see Ch. III.

Hematite. Tends to be common only where sediment is 'sealed', or where infiltration of meteoric water is prevented by impervious cover, otherwise rapidly hydrated to limonite.

Hercynite. The iron-spinel of rare occurrence and doubtfully recorded in sedimentary rocks.

Heulandite. A mineral which, owing to its comparative softness, is likely to be rare as detrital. Provenance is usually drusy basalt associated with other zeolite minerals.

Hiddenite. See under *Spodumene*.

Hornblende. Sometimes a difficult mineral to interpret; is freshest in 'sealed' deposits, much chloritized in porous sediments; the brown variety seems to be much less stable and may be a criterion of geologically recent formations; ~~green hornblende has a much greater time-range and would seem to be favoured by marine environments, e.g. Ordovician, Upper Lias-Inferior Oolite, Portland Sand, Aptian, Eocene, Miocene, Pliocene.~~

Humite. Scanty records in sediments indicate derivation of this mineral from dolomitic limestone, especially in contact-altered zones where magnesium silicates have developed. A rare species and to be anticipated only in favourable environments in which such provenance is in evidence.

Hyalite. See under *Opal*.

Hypersthene. As for *Enstatite* (*q.v.*).

Iddingsite. A rare species as yet recorded only from river sands and certain soils. Unstable in acid environments.

Idocrase. See under *Vesuvianite*.

Ilmenite. 'The titanium minerals are ... closely connected with one another, and transformations are possible in almost every direction (F. W. Clarke, *Data of Geochemistry*, 1924, p. 355). This concerns ilmenite, anatase, rutile, brookite, titanite, leucoxene, possibly perovskite and locally pseudo-brookite. *q.v.* Majority of anatase grains are authigenic, *i.e.* generated *in situ* at the expense of ilmenite or other titanium species; brookite is sometimes authigenic, though it alters to rutile in suitable environments; its comparative scarcity may be due to this fact, much of the large, ill-shaped, dirty-brown rutile possibly representing this reaction; rutile is both derived and authigenic, similarly titanite and leucoxene; the geochemical mechanism of these transformations may be reasonably clear, but the selective operation of any particular tendency in a sedimentary environment is not so obvious and requires investigation. The ilmenite-leucoxene ratio alters in favour of the latter with increasing geological age of the enclosing sediment, but seems to bear little relationship to the occurrence of the oxides or titanite;

a reciprocal relationship has, however, been noticed between titanite on the one hand and anatase and brookite in the same deposit on the other (P. G. H. Boswell, *Geol. Mag.*, 1924, p. 267). 'Biotite altering beneath a capping of turf and in a sour water environment is likely to undergo complete disintegration, and it appears at least possible that (a) its decomposition products include a more or less colloidal complex of titania and silica, and that (b) the silica and titania may slowly disengage themselves and become crystalline: the silica may expend its potential energy in repairing and extending quartz grains, or in initiating new ones; in a similar way, titania may apply itself to anatase. It is also possible that the alteration of ilmenite to granular anatase proceeds via a complex of hydrated ferric oxide and hydrated titania, and anatase nuclei thus authigenically produced could receive extensions in the manner suggested above' (A. Brammall and H. F. Harwood, *Miner. Mag.* 20, 1923, p. 24). The instability of allothigenic biotite under certain sedimentary conditions is capable of initiating a similar mechanism and enquiry into the provenances of British sediments rich in transparent titanium minerals in most cases points to the presence of sufficient black mica for the purpose in the parent-rocks concerned. The development of anatase is facilitated by high porosity and ill-graded sediment, implying facility of 'sour water' circulation. The generation of leucoxene and titanite (according to A. Cathrein synonymous terms—see *Zeitschr. Kryst. Min.*, 6, 1882, p. 244) suggests a similar environment and it is observed that leucoxenic alteration is at a maximum in coarse sediments; authigenic titanite may be initiated with the formation of titanium-bearing chloritic minerals from decomposed amphibole-rich parent-rocks, since chlorite is often observed in concentrates in which titanite is conspicuous; the presence of lime is, of course, essential. Where lime is absent or at a minimum, especially in an iron-rich environment, the ilmenite—rutile—anatase—brookite tendency (in order of decreasing frequency) seems to predominate; in a neutral environment the leucoxene—titanite—perovskite tendency may be strong, but there is difficulty of achievement, certainly of persistence, in the case of the two latter species, attested by their scarcity in detrital deposits; alternatively, they may be formed initially in a sedimentary environment, but owing to chemical instability or unfavourable 'atmosphere', the titanite—rutile—ilmenite tendency may be promoted. More observations of the occurrence and association of the titanium minerals in all kinds of sediments is needed before their individual or collective significance can be fully appreciated.

Indicolite. See under *Tourmaline*.

Iridosmine. This alloy of varying quantities of Ir and Os is found with *Platinum* (q.v.), in basic and ultrabasic igneous rocks and occurs detrital chiefly in alluvial deposits, beach sands, etc. It is hard, very stable and resistant to chemical weathering and alteration.

Jasper. See under *Chalcedony*.

Kaolinite. Known chiefly as an alteration product of feldspathic minerals, sometimes by pneumatolysis, but in sediments by the action of humic acid (if near the surface) or of percolating water and carbonic acid. Frequently accompanied by sericitic mica. Rare as an individualized

mineral in sediments; usually noted as a decomposition product in deposits which are ill-graded or 'open'; is not confined to, and is often totally absent from, argillaceous rocks. (See R. Schwarz and R. Walcker, *Zeit. f. anorg. chem.*, 145, 1925, p. 304.) Some records of *Kaolinite* may be *Dickite* (q.v.).

Kunzite. See under *Spodumene*.

Kyanite. A stress mineral. Chemically stable and resistant to acidic percolating waters (more so than andalusite or sillimanite in sediments), to which its remarkable persistence may be ascribed. Susceptible of disintegration under mechanical stress and may thus be an indicator of the intensity of the forces implied, largely due to its prevalent cleavages.

Labradorite. In certain circumstances prone to decomposition by percolating waters charged with carbon dioxide, whereby calcite and free silica are formed. Other forms of alteration (sometimes detected in partial phase in isolated grains) include sericitization or kaolinization. 'Saussuritization' (p. 134) is prominent with labradorite derived from basic igneous rocks (e.g. gabbro). Seldom survives 'fresh' in sediments far removed from parent-rocks.

Lawsonite. Probably of wider spread occurrence in sediments than records imply. Generally secondary, derived from lime-soda plagioclase, especially in 'saussuritized' gabbro environments. Occurs in gneisses and schists. A normal mode of development would appear to be by hydration of anorthite.

Lepidolite. In detrital deposits may be primary or secondary after muscovite (q.v.).

Lepidomelane. Iron-rich *Biotite* (q.v.).

Leucoxene. See under *Ilmenite*.

Limonite. Commonly implies oxidation and hydration of iron-ores such as pyrite, pyrrhotite, marcasite and is also formed from magnetite, hematite, ilmenite and other iron-bearing minerals. Oxidation of sulphidic iron-ores produces firstly soluble sulphate, afterwards precipitated as hydroxide; process aided by carbonic acid in percolating water; organic acids also potent in this respect. In detrital sediments limonitization proceeds where the rocks are porous and where iron-bearing solutions have ready access to them; or in a 'sealed' environment alteration of original iron sulphides or oxides may take place slowly. Limonite in detrital sediments is frequently prolific in proximity to glauconite-bearing rocks, implying the formation by alteration of the glauconite. Limonite is so ubiquitous in sediments and its genesis is so varied, that in the absence of other evidence it is seldom of any special significance.

Maghemite. A low temperature oxidation product of Magnetite or by dehydration of Lepidocrocite, found in gossan. Some of the brown tarnished magnetite noted in detrital deposits suitably situated to weathered gossan, may represent this mineral, but it is relatively uncommon.

Magnesite. Implies formation by (a) decomposition of ultrabasic igneous rocks such as peridotite, serpentine, by action of water charged with carbon dioxide, (b) replacement of existing limestone (calcium by magnesium), (c) chemical precipitation in which magnesia-bearing

solutions are in contact with carbonates. Presence in sediments (or associated with them) more often than not implies subaerial, as distinct from marine conditions of formation.

Magnetite. Pure magnetite is far less common in detrital sediments than is generally thought; usually it is detrital, but it may also result from alteration of marcasite and pyrite (C. R. Van Hise) or from the oxidation of siderite. It is most characteristic of fine-grained, semi-porous deposits where infiltrating solutions are less potent.

Marcasite. The unstable isomer of pyrite and nearly always authigenic. Best preserved in a neutral environment or in the presence of lime; its organic origin is frequently suggested by its occurrence in association with fossil shells almost invariably in marine deposits; an hermetically 'sealed' environment aids its preservation.

Melanite. The rare titanium-bearing garnet (also known as 'schorlomite') known particularly in alkali syenites (*e.g.* Assynt complex, Scotland) from which rock-type its derivation in sediments may be inferred. Frequently accompanied by feldspathoid minerals, *e.g.* nepheline (the latter probably represented in sediments by its decomposition product 'cancrinite').

Microcline. A valuable indicator of climatic conditions attending deposition of the sediment in which it occurs (p. 431).

Molybdenite. Provenance is commonly granite, pegmatite or aplite, where it occurs as an accessory mineral. While chemically stable, it is mechanically weak and does not survive long distance transport (*e.g.* in stream deposits, R. Caldew Valley, in vicinity of Carrock Fell and Caldbeck Fell, Cumberland, but not far downstream).

Monazite. The alteration of this mineral to an aggregate in which cerium oxide is conspicuous tends to be superficial, but in deposits of geological age seems to proceed under conditions implying humid, estuarine environment; fresh, unaltered monazite, though characteristically 'worn', is of little significance other than of provenance.

Montmorillonite. Particularly characteristic of deposits such as Fuller's earth. A complex hydrated aluminous silicate produced by alteration of mica, feldspar, etc. Possesses marked adsorption and base-exchange capacities. See Ch. III.

Muscovite. When detrital, its disproportionate size relative to associated constituents is noteworthy and significant of its buoyancy, especially in an aqueous medium. May be authigenic, formed from feldspar, topaz, andalusite; or may represent certain feldspathoid minerals. Some muscovite observed in sediments represents bleached biotite (cf. optical properties), implying action of acidic solutions, whereby iron oxide and alkalis are removed and hydration promoted. *Sericite* is invariably secondary and is a stress mineral; white mica is more prolific in fluvatile and estuarine arenaceous sediments than in similar deposits of marine origin or conversely in marine, rather than in fluvatile or estuarine clays. *Nacrite.* A product of erosion of ore deposits; also authentically recorded in hydrothermal bodies. A clay mineral, seldom reported from coarse clastic sediments; soft, unstable and rare.

Nepheline. A prominent constituent of nepheline syenite and phonolite, from which it may be locally derived in recent drift deposits. It is

prone to alteration to *Zeolites* and *Cancrinite*, sometimes to *Mica* and is thus somewhat unstable.

Nephrite. As for *tremolite* or *actinolite* (q.v.).

Nontronite. A rare alteration product characteristic of certain residuary clays often associated with montmorillonite, beidellite. In some cases it may be indicative of original alkaline petrographic province. May also be derived from wollastonite.

Oligoclase. Probably the most stable of the plagioclase feldspars in surviving the sedimentary cycle, kaolinization being less common than with albite or andesine. Under hydrothermal conditions, the normal change is to sericitic mica. In sediments it is inferential of sub-acid and intermediate igneous rock provenance.

Olivine. Fresh, unaltered detrital olivine is rarely, if ever, found in sediments of geological age, decomposition to one of the chlorite species (e.g. in serpentine), steatite, epidote, etc., being easily achieved, especially in a hydrous environment. It is thus characteristic only of Recent deposits (shore sands and alluvials) not far removed from source of origin. Essentially an anti-stress mineral.

Omphacite. As for *Diopside* (q.v.).

Opal. Invariably of secondary origin implying a reconstitution of certain rock-forming silicates under stress of hydrothermal metamorphism; or deposited from solution in 'hot spring' environments. May be of organic origin, e.g. land plants, freshwater sponges and diatoms or marine sponges and diatoms, in recent deposits and soils (F. Smithson).

Orthoclase. A valuable indicator of climatic conditions attending deposition of the sediment in which it occurs. Does not long survive a hydrous environment, especially if percolating waters are acid or if any associated sulphide ores are undergoing oxidation whereby acid may be liberated *in situ*. Meteoric water containing carbon dioxide also attacks it. Such alteration is usually indicated by the presence of kaolinite, mica or hydrous silicates of alumina; mica will not be formed if alkalis have been removed. In the presence of lime and iron, epidote or zoisite may form. An anti-stress mineral. The variety *Sanidine*, when identified in sediments, suggests derivation from acid volcanic rocks, e.g. rhyolite, trachyte, etc.

Ottrelite. Essentially a product of schists and phyllites, but apparently (from the records) less stable than chloritoid; consequently it does not persist long in sediments. Tends to alter to one or other of the chlorite group of minerals.

Palladium. Derives from ultrabasic igneous rocks, associated with native platinum and base metal ores. Found as granules in alluvial deposits. It is chemically stable but rare.

Penninite. Invariably of secondary origin, generally the product of hydrothermal alteration of aluminous ferro-magnesium minerals such as augite, hornblende, biotite, epidote, etc.

Periclase. A rare species tending to alter easily to hydro-magnesite or chloritic minerals. In other hydrous environments, brucite is formed.

Perovskite. An accessory mineral in certain basic igneous rocks, especially those containing *Nepheline*, *Mellite* or *Leucite* (Dana). It

may be a secondary product of alteration of *Ilmenite*. It is a comparatively rare mineral in detrital deposits, only to be anticipated in favourable parent-rock environments.

Phenacite. Provenances are granite pegmatite; metamorphic rocks; mineral lodes. Found detrital in localized alluvial deposits (e.g. Minas Geraes, Brazil). A stable but very rare species.

Phlogopite. Occurrence in sediments generally implies release from dedolomitized crystalline limestone. Commonly associated with forsterite and diopside in such circumstances.

Picotite. Of no apparent significance save as an indicator of parent-rocks.

Piedmontite. A rare species derived principally from schists and gneisses; often of secondary origin.

Platinum. Parent rocks are ultrabasic, e.g. norite, gabbro, peridotite, dunite, serpentine. More rarely in nickel-sulphide ores and quartz veins. Found detrital in alluvial and beach deposits. Extremely stable and persistent.

Pseudobrookite. 'Pseudobrookite commonly occurs as a pneumatolytic or fumarolic product in volcanic igneous rocks and as a reaction product in such rocks'. (Dana, 7th ed.). Rarely detrital.

Psilomelane. Indicates derivation from secondary manganese deposits and commonly associated with pyrolusite. Often occurs with sedimentary iron-ores from which provenance it is frequently traceable in sediments in which it is identified.

Pumpellyite. A rare species only comparatively recently reported from detrital sediments (Ch. I, p. 166). Derived from volcanic rocks, e.g. amygdaloidal basalt; also from glaucophane schist.

Pyrite. Is most characteristic of impervious clays, shales and muds where it is usually authigenic and suggestive of organic origin. In a reducing environment, especially under marine conditions, sulphates are converted to sulphides by the decomposition of organic matter; in the presence of CO₂ sulphuretted hydrogen is formed which, by reaction with iron silicates, forms pyrite, marcasite, etc. Alternatively, bacterial influence may account for the H₂S. The frequent occurrence of pyritized casts of micro-organisms is suggestive of the mechanism above outlined. The occurrence of pyrite bears an interesting relationship to the colour of the sediment containing it, whereby considerable light may be thrown on the environment of sedimentation: it is rare in red rocks, usually inferential of oxidizing conditions and frequently the colour of terrestrial (fluvial and aeolian) deposits; it is sporadic in blue or bluish-grey rocks, especially clays, usually suggestive of reducing reactions in excess of oxidizing influences; it is most common in black or blackish-grey clays or muds formed in a reducing environment, often implying biochemically toxic conditions; in green rocks it tends to be rare or absent where the colour is due to chloritic products (resulting from decomposition of ferro-magnesian minerals), in which case the chloritic matter is apparent; more common where the colour is due to glauconite. These circumstances are exemplified by the Stockdale Shales (Silurian) of the Lake District (J. E. Marr, *Quart. Journ. Geol. Soc.*, **81**, 1925, p. 113), where benthonic organisms are absent in the black muds (pyrite and

carbon common), rare in the green and some of the red muds, fairly abundant in the blue and part of the red muds; absence, rarity or observed dwarfing of these organisms is ascribed to toxic influences, sulphuretted hydrogen or iron hydrate. Thus pyrite, apart from its own significance, should be interpreted in conjunction with organic evidence if available; this mineral, together with its oxidation products, will frequently throw a flood of light on the nature of the environment from both biological and geological points of view.

Pyrolusite. A product of infiltration, usually observed on joint planes of calcareous rocks. In some cases it may be traced to swamp deposits associated with limonite, from which it is transported into underlying rocks by descending meteoric waters, but often its origin in sediments is obscure.

Pyrope. Occurrence in sediments suggests derivation from ultra-basic igneous rocks. Does not tend to survive far after release from parent rock, being readily altered to kelyphite (sometimes a fibrous intergrowth of amphiboles and feldspar, but often a complex mixture of amphiboles and pyroxenes). In anhydrous environments tends to alter to one or other of the chlorite group of minerals. Most commonly confined to alluvial deposits not far removed from source of origin.

Pyrophyllite. One of the kaolinite group of minerals occurring chiefly in crystalline schists. Comparatively rare in sediments.

Pyrrhotite. The origin of this mineral in detrital sediments is not always clear, but it tends to occur only in 'sealed' sediments beyond the reach of oxidizing or acidic waters of meteoric origin, though it is itself almost invariably authigenic; probably formed as a result of biochemical processes.

Quartz. This essential mineral of detrital deposits is significant of environment chiefly by reference to its form (nature and degree of abrasion), while a study of its inclusions is often of prime importance in tracing the source of the deposit concerned.

Riebeckite. A rare, unstable soda-bearing amphibole which tends rapidly to alter with release from parent rock. It is consequently rare in sediments of geological age, but may be expected to persist in recent deposits, especially in detrital deposits protected from aqueous infiltrations.

Romeite. Derived from mineral ore bodies, sometimes associated with manganese and epidote. Found detrital in eluvial sands at Tripuhy near Ouro Preto, Brazil, one of the notable sources. Superficially alters to a sulphur-yellow encrustation, possibly an Sb compound. Rare and decidedly localized.

Ruby. See under *Corundum*.

Rutile. See also under *Ilmenite*. Rutile is a possible stress mineral. Perfect euhedral forms in detrital sediments are probably authigenic, but derived rutile, often much fractured, is met with universally and particularly in aeolian deposits.

Sanidine. See under *Orthoclase*.

Sapphire. See under *Corundum*.

Scheelite. Crystalline igneous rocks, granite, pegmatite and aplite, some contact-altered limestones and metalliferous veins, all contribute

to the detrital occurrences of this mineral. Characteristic occurrence as small pebbles and grains in eluvial deposits, generally not far removed from source. Mechanically rather weak due to cleavage, chemically liable to alter to wolframite, but the reverse can happen as a result of hypogene processes (Dana).

Selenite. The crystalline form of gypsum is particularly characteristic of clay environments where it persists either as individual crystals or more commonly as complex clusters of twinned types. With the weathering of the clay, crystals rapidly disintegrate on account of their soft and hydrous character. In other environments, it can suffer dehydration to anhydrite or more rarely reduction to native sulphur. See also under *Gypsum*.

Serpentine. See remarks in Chapter I, p. 177, and refer to *Antigorite* and *Chrysotile*.

Siderite. Frequently significant of a fluviatile or lacustrine environment, especially in fine silts and clays in which vegetable organic matter is present. Infiltrating waters charged with carbonic acid may, in the presence of organic matter, result in the formation of siderite, though in porous rocks calcite and limonite are the more likely products. E. Spencer suggests another mechanism (*Quart. Journ. Geol. Soc.*, **81**, 1925, p. 687), 'that the iron compounds present in solution as soluble carbonates, humates or hydrolized and possibly colloidal hydrates, were absorbed by the fine-grained and partly colloidal sediments, and carried down with them during deposition'. Clay-ironstone is a precipitate deposit tending to form about organic nuclei under terrestrial (as opposed to marine) conditions. Oolitic forms of siderite are frequently accompanied by the mineral chamosite, an iron silicate, as in the Cleveland deposits (*Sum. Prog. Geol. Surv. Gt. Brit.*, 1922; A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Res. Gt. Brit.*, **29**, 1925) and imply weak carbonation; strong carbonation is productive of clay-ironstone; spherulitic siderite can only be produced in the absence of chamosite (E. Spencer). Thus a detailed study of siderite in sediments may be highly suggestive of their mode of formation and environment. (See also J. H. Taylor, *Petrology of the Northampton Sand Ironstone Formation*, *Mem. Geol. Surv.*, 1949.)

Sillimanite. A highly stable species, but of little significance save as an indicator of provenance.

Sodalite. A rare detrital mineral derived from alkaline igneous rocks and seldom found far from source.

Spessartite. Rare in sediments, but may occur where certain types of schists or rhyolite contribute to their formation. In some environments is known to alter readily to biotite.

Sphalerite (Zinc Blende). Tends to localize the deposit in which it is found. E. F. Newton draws attention to its unusually abundant occurrence in roughly rounded aggregates up to 0.25 mm. in diameter in the Cretaceous Fuller's earth of Surrey and to its rarer occurrence in the Jurassic earths of England (*Proc. Geol. Assoc.*, **48**, 1937, pp. 179, 184). H. H. Thomas also noted the occurrence of zinc blende and galena in the English Mesozoic clays and stated that 'where these two sulphides are met with, they always occur surrounding or replacing the

soft part of some organism' (*Geology of Ore Deposits*, 1909, p. 328). He further pointed out (*op. cit.*, p. 321) that zinc sulphide is normally precipitated in alkaline solutions, but under increased pressure may also be produced in a feebly acid one.

Sphene (Titanite). See under *Ilmenite*.

Spinel. Highly stable species in sediments generally implying derivation from crystalline limestone or schist. See also under *Ceylonite*, *Picotite*, *Chromite*, *Magnetite*.

Spodumene. The lithia-bearing pyroxene, chiefly significant for its association with coarse pegmatites to which source its origin in sediments may often be traced. Very susceptible to alkaline solutions by which it is changed into albite, muscovite, etc. An anti-stress mineral. *Hiddenite* is the rare emerald-green, *Kunzite* the lilac variety.

Staurolite. A stress mineral. Is frequently suggestive of provenance, but is independent of facies and not inferential of any particular sedimentary environment. Pre-Armorican record from Llandovery (Silurian) of the Midlands (P. G. H. Boswell).

Steatite (Talc). Occurs chiefly in schists associated with chlorite minerals and iron ores. Also occurs in serpentine rocks as veins and filling cavities from which it is easily released to contribute to nearby recent sediments.

Stilpnomelane. This complex species is invariably associated with sedimentary iron ores or iron ore veins, whence derived. Its extreme softness renders it mechanically unstable and its identification in sediments indicates proximity to source of origin.

Strontianite. A local species to be anticipated only in environments where the mineral is known in veins (generally in limestone).

Sulphur. To be anticipated in sedimentary deposits where it occurs as a sublimate in volcanic regions, particularly where subject to recent activity. Also prevalent in gypsum deposits in similar environments or may be traceable to hydrogen sulphide emanations, mineral springs, crude petroleum or other bituminous matter.

Talc. See under *Steatite*.

Tantalite. See under *Columbite* Ch. I, p. 87.

Thorianite. Derived principally from granite-pegmatite veins but well preserved in certain gem gravels (*e.g.* Balangoda, Ceylon). 'Alters readily by hydration and oxidation of the uranium, the final product being a grey, yellow or brown gummite-like substance' (Dana, 7th. ed.).

Note.—Gummite is a field term denoting a mixture of hydrated oxides of uranium with Pb and Th, of doubtful identification.

Thulite. As for *Zoisite* (*q.v.*).

Thuringite. A rare mineral found in association with iron ores and garnet; a member of the Chlorite group of minerals. Undergoes alteration easily to hydrated oxide of iron (*Limonite*).

Titanite (Sphene). See under *Ilmenite*.

Topaz. Frequently occurs under the same conditions as andalusite, but is more stable than that mineral and has a wide stratigraphical range; noted in Upper Silurian deposits. In an alkaline environment (infiltrating alkali-bearing solutions) a change to muscovite (damourite or sericite type) is possible.

Torbernite. A rare secondary mineral found in association with other secondary uranium minerals deriving from oxidation of *Uraninite*.

Tourmaline. An ubiquitous detrital species on account of its stability, though under certain conditions is liable to micaceous and chloritic alteration. May survive more than one erosional cycle, when its worn character, together with other criteria may be significant. In some cases there is reason to believe that this mineral is authigenic. *Indicolite* is a local indigo-blue variety.

Tremolite. A stress mineral, sometimes replacing pyroxene; is not so stable as ordinary hornblende and does not survive prolonged transport or re-deposition; hence it tends to localize the deposit in which it occurs.

Uraninite. According to Dana (7th. ed.), uraninite may have four different sources of origin, granite and syenite pegmatites; high temperature tin veins; hydrothermal Co-Ni-Bi-Ag-As veins of moderate temperature formation; hydrothermal sulphide veins. Easily altered: see detailed account in Dana (7th. ed., p. 615).

Uvarovite. A rare mineral in sediments. Derived from ultrabasic-igneous rocks (usually chromium-bearing) or contact-altered limestones, but readily alters to chrome-bearing chloritic matter in hydrous environment.

Vesuvianite. A contact-altered limestone species associated particularly with grossularite, wollastonite and epidote and stable in sedimentary deposits derived therefrom.

Viluite. As for *Vesuvianite*.

Wolframite. Essentially a pneumatolytic vein species generally associated with cassiterite; stable but superficially weathering brown in detrital deposits.

Wollastonite. A contact-altered limestone species often associated with diopside, garnet, epidote and readily altered to calcite.

Xenotime. A problematical species in detrital sediments on account of the difficulty in its certain diagnosis; may be anticipated where monazite is prevalent, but has little other significance.

Zircon. An almost invariable accessory mineral in detrital deposits and, like tourmaline, may survive several erosional cycles; colour, zoning and inclusions are significant of provenance. See also under *Biotite*.

Zoisite. A stress mineral to be anticipated in association with hornblende, glaucophane, epidote, etc., and probably more common in sediments than usually supposed.

PRODUCTS OF SEDIMENTATION INFLUENCING PALAEOGEOGRAPHICAL PROBLEMS

An understanding of the mechanism of processes involved in a sedimentary cycle is an essential preliminary to interpretation of the products themselves. On first principles, this mechanism implies weathering, erosion, transportation, some chemical differentiation and ultimate sedimentation. Thus a given sediment seldom if ever represents a faithful 100% counterpart of the parent rocks

from which it has been derived. Much mineral matter may seemingly be lost, or at least changed into a form dissimilar from original species, during the release-sedimentation phase of the cycle. Mineral matter is theoretically indestructible under normal conditions, but a great deal happens to it during the birth of a sediment.

V. M. Goldschmidt has discussed the geochemical aspects of the cycle and outlined a procedure for calculating the total amount of sediments and clastic deposits, limestone and dolomite separately¹.

More recently B. Mason has described Goldschmidt's processes and conclusions in his valuable textbook². Summarily, the steps in the geochemical separation which happens during formation of a sediment are:

- Stage 1. Minerals resistant to chemical and mechanical breakdown, *e.g.* quartz. End product: *sandstone*.
- Stage 2. Chemical breakdown of aluminosilicates, *e.g.* feldspar. End product *mud: i.e.* clay minerals.
- Stage 3. Contemporaneous with formation of mud, or may be separated in space and time, is release of iron as ferric hydroxide, implying oxidation from ferrous to ferric state, then hydrolysis. End product: *ferruginous rocks and iron ores*.
- Stage 4. Inorganic precipitation of calcium as calcium carbonate or by organisms or both. End product: *limestone*. Conversion of limestone to dolomite, wholly or in part, by metasomatic action of magnesium-rich solutions. End product: *dolomite*.
- Stage 5. Remaining bases in solution accumulate in the ocean from which, by evaporation saline deposits are formed. End product: *salt and other chemical deposits*.

Thus, as V. M. Goldschmidt pointed out, the whole process of sedimentary rock formation as influenced by the major rock-forming minerals during sedimentation, simulates a quantitative chemical analysis; it is in fact the normal procedure adopted in silicate analysis (see Vol. I, Ch. VIII).

It is noted that the foregoing scheme does not include such organic materials as coal and oil; these are special cases of hydrocarbon concentration brought about by quite different geochemical processes.

¹ V. M. Goldschmidt, *Grundlagen der quantitativen Geochemie, Fortschr. Mineral. Krist. Petrog.*, 17, 1933, pp. 112-156.

² B. Mason, *Principles of Geochemistry* (Wiley, New York), 1952, p. 150.

The reader is advised to consult the two authors quoted above for further details of these fundamental conceptions. These geochemical aspects of any problem of palaeogeographical reconstruction are essential factors to take into consideration in the course of such research work.

CHAPTER VII

THE APPLICATION OF SEDIMENTARY PETROLOGY TO THE STUDY OF SOILS AND RELATED SUPERFICIAL DEPOSITS

DOROTHY CARROLL, PH.D., D.I.C.

Introduction—Soil Formation and Weathering—Examination of Soils—Examples of Soil Mineralogical Studies—Weathering and Soil Development Studies—Mechanical Composition of Soils and its Use in Soil Mineralogical Studies—Related Superficial Deposits—Future Research in Soil Mineralogy—Bibliography

INTRODUCTION

ALTHOUGH identification of mineral grains in soils has been studied to some extent from the beginning of the twentieth century, particularly by the Dutch, it is only since the mid-1930s that the science of soil mineralogy has assumed importance and recognition. There is now a considerable volume of published work in this field which overlaps into that of sedimentary petrology on the one hand and into soil science on the other. It is proposed in this chapter, firstly to give a brief outline of the methods used in soil mineralogy, then to describe some of the investigations which have been made in various parts of the world, and finally, to indicate lines of future enquiry and techniques in this branch of applied sedimentary petrology. Information about the clay minerals will be found in Ch. I and particularly in Ch. III; such minerals will only be given passing reference here, although they are very important in soil development studies.

SOIL FORMATION AND WEATHERING

Soils, forming as they do, the outermost part of the crust of the earth on which we live, from which we obtain all our chemical requirements except oxygen for the maintenance of life, are, for us, the most important materials which exist. Geologically, too, soils are important, in that they are the materials, produced by various weathering processes which, if subject to erosion, will

form new sediments after transportation and deposition. A study of soils includes, therefore, a study of weathering processes, largely chemical, but also mechanical.

A soil is formed from a rock or rocks, using this term in its widest geological sense, and is an expression of the interaction of five variables, known as factors of soil formation, at any particular locality. These are: parent material, climate, biological activity, relief, and time¹.

A soil is that part of the earth's crust in which plants grow. If a vertical section from the surface of a soil to the underlying rock is examined, it usually shows an arrangement of horizontal layers. This section through the soil is known as the soil profile, and the horizontal layers are soil horizons (Fig. 74 and Pl. 66). It is upon the observed differences in composition and arrangement of these horizons that soils are described and classified; while we are not concerned here with soil classification except in its broadest aspects, it should be realized that soils can be placed in a number of large groups, known as the Great Soil Groups². There are a number of well-defined soil-forming processes, always dependent, however, on the above five factors, which leave their imprint on these large groups of soils, *e.g.* podzolization, calcification, lateritization, salinization, peat formation and the effect of poor drainage (gleying). Probably the factor of greatest importance in soil formation is the amount and pH status of the water which passes through the material in which a soil is forming, *i.e.* the water from rainfall which seeps through the weathering rock. This water, acting upon the parent material, is responsible for mineralogical changes within the mineral and organic complex which is the soil and it is these changes which are investigated by soil mineralogists. The degree of profile development, as shown by the presence of soil horizons, is dependent on the activity of the different soil-forming factors, and on their intensity.

The weathering rock produces the C horizon (Fig. 74) or parent material, because of the impact of the weathering processes at work in the environment in which it is situated. Whether this C horizon will be changed chemically or mineralogically from that of the underlying material will depend on whether mechanical or chemical processes are active, *e.g.* under glacial conditions mechanical disintegration is the more important; under tropical conditions, the chemical alterations are the more important. Another factor to be considered here, too, is the state of aggregation of the

¹ H. Jenny, *Factors of Soil Formation* (McGraw-Hill, New York), 1941.

² G. W. Robinson, *Soils: their Origin, Constitution and Classification*, 3rd ed. (Murby, London), 1950; Soils and Men, U.S. Dept. of Agriculture, Yearbook for 1938.

underlying rock; a sandstone will disintegrate into material of its original grain-size, which may be very different from the behaviour of a granite, for instance. The parent rock itself is merely 'a relatively inert storehouse of future soil material'¹, but it gives the original chemical composition to the developing soil and is responsible, upon disintegration, for the relative quantities of different sized grains which determine the soil texture. C. C.

SOLUM OR TRUE SOIL	ZONE OF ELUVIATION	A ₀	ORGANIC DEBRIS
		A ₁	DARK COLORED, MIXED ORGANIC AND MINERAL
		A ₂	LIGHT COLORED, ZONE OF MAXIMUM LEACHING
		A ₃	TRANSITIONAL TO B. MORE LIKE A THAN B
	ZONE OF ILLUVIATION	B ₁	TRANSITIONAL TO B MORE LIKE B THAN A
		B ₂	A DEEPER COLORED HORIZON ZONE OF MAXIMUM ILLUVIATION
		B ₃	TRANSITIONAL TO C
	WEATHERED PARENT MATERIAL	C	WEATHERED MATERIAL FORMED FROM D
	UNDERLYING STRATUM	D	SOLID OR UNCONSOLIDATED "ROCK" IN GEOLOGICAL SENSE

FIG. 74. Schematic diagram of a soil profile showing the various horizons and their relation to one another and to the parent rock (from *Soils and Men*, U.S. Department of Agriculture Yearbook, 1938).

¹ *Soils and Men*, *op. cit.*, p. 949.

Nikiforoff¹ describes how the parent material and underlying rock act as this storehouse, from which the soil slowly renews itself from below as it is depleted at surface by erosional forces.

From these points of view then, the parent mineral matter, the soil mineral matter and the original size distribution of soil particles, soil mineralogy can supply much useful and interesting information. Both inherited and acquired mineralogical characteristics are worthy of examination.

The mineralogical investigations of soil which have been made fall into three broad groups: (1) examination of mineral grains in the sand and silt grades; (2) investigation of weathering and soil-forming processes as exemplified by the kinds and quantities of minerals present and their relative proportions in different parts of soil profiles; and (3) qualitative and quantitative identification and study of the clay minerals. These three groups naturally overlap in their fields of investigation.

Mineralogical investigations in the first group show whether a soil is derived from the rock beneath it (residual or autochthonous) or is of mixed origin (transported, transported mixed with residual material); they indicate the reserve of mineral grains in the soil which may alter, during soil-forming processes, to provide chemical elements for plant growth; and the size distribution, or mechanical composition, indicates soil texture, an important characteristic of any soil, which may also serve to indicate parentage. Such mineralogical investigations have made important contributions to our knowledge of soil fertility, particularly in tropical regions and where nutritional disorders of plants and animals have been encountered. The differentiation of soils mineralogically according to parentage is a useful application in the mapping of soil types in the field.

In the second group, weathering and soil-forming processes are studied in the various horizons of a soil profile, by as many techniques as are available, in order to give an explanation of soil development in any particular environment. Some of these techniques are: mechanical analysis, chemical analysis, mineralogical examination by microscopic, X-ray, and differential thermal analysis. The results are combined to give a picture of the genesis of a soil. The formation of soil is the first stage in the development of new sedimentary rocks; it is the beginning of a cycle of erosion and of sedimentation; the mineralogical facts learned from soils will give information about the availability of the different kinds of mineral matter in the area being eroded. Questions arise such as: will the streams carry kaolinite or micaceous clay minerals

¹ Weathering and Soil Evolution, *Soil Sci.*, 67, 1949, p. 219.

from the area? Are the resistant minerals such as zircon and tourmaline concentrated in the soil before being removed by erosion? What is the effect of soil-forming processes on the stability of such minerals as feldspar or amphibole?

The clay minerals of the third group are not discussed here; their identification and quantitative estimation are given in Chs. I and III (this volume).

These are some of the problems to which soil mineralogy can give an answer. The investigations listed under (1) above are the more immediately practical and economic aspects of such studies; those listed under (2) involve geological theories and are not so immediately practical, but any such increase in our knowledge of geological processes is important.

Investigations of unconsolidated sediments involve grain size and mineralogy, and have as their objects elucidation of origin or provenance of the materials. Loess, volcanic ash, unconsolidated sands of dunes, beach sands, river sands, desert sands and other sandy deposits belong here.

EXAMINATION OF SOILS

Various methods of laboratory technique will now be discussed; some of these have already been described in earlier chapters¹, but are repeated here because they have been adapted and sometimes modified for soil investigations.

It is first necessary to describe the kinds of samples required for examination. For results of any investigation to have value, soil samples should be collected, where possible, as samples of recognizable horizons in a soil profile. The most satisfactory samples are those obtained from a pit dug to expose the whole profile, or from clean road-cuts where the soil shows that it has not been disturbed. Soil-augurs or post-hole diggers give, with care, very good samples and the thickness of each soil horizon can usually be obtained. Each sample should be large, at least 1-2 lb. in weight, and it should be collected in a canvas bag, jar, or other suitable container; care should be taken in the drying of wet samples. Air-drying is preferable to heating in a drying oven. A sample of the C and D horizons (Fig. 74, p. 459) should always be collected if possible. The advantage of a large sample is that there is ample material to work with, especially if it is intended to make an exhaustive investigation. It is hardly necessary to add that the position of a sample in the field should be definitely fixed on a map.

Various procedures have been adopted for the examination of soils by different investigators for different purposes.

¹ Vol. I.

A. Mechanical Composition. Details of methods of making mechanical analyses are given in Vol. I, Ch. IV. For very sandy unconsolidated materials, sieving through a standard set of sieves with a fixed ratio of aperture openings is all that is required. Experiments have been carried out¹ on optimum time for sieving and it is generally agreed that 10–15 minutes on a Ro-Tap or similar mechanical shaker gives maximum efficiency. Hand-sieving is to be preferred in some circumstances, but where large numbers of samples are required, hand-sieving is impracticable unless much cheap labour is available. For 8-in. diameter sieves, less than 100 gm. sample is not a satisfactory amount.

The mechanical analysis of a soil should be made by one of the standard pipette methods in which the dispersion of the clay fraction is effected by an electrolyte (sodium hydroxide, ammonium hydroxide, sodium metaphosphate, etc.), and the sample is shaken mechanically for certain periods of time, four to six hours for example, to ensure complete dispersion. The method used by many soil laboratories is described by C. S. Piper² and the U.S. Bureau of Soils method by V. J. Kilmer and L. T. Alexander³.

In the International method of soil mechanical analysis the fractions of the soil obtained are:

Coarse sand	2–0.2 mm.
Fine sand	0.02–0.2 mm.
Silt	0.002–0.02 mm.
Clay	< 0.002 mm.

This does not give sufficient grades of material for statistical use of the data according to standard sedimentary petrological procedure (W. C. Krumbein and F. J. Pettijohn⁴). A better method is that of the U.S. Bureau of Soils in which the following classes are obtained:

Stones	> 2 mm.
Gravel	2–1 mm.
Coarse sand	1–0.5 mm.
Medium sand	0.5–0.25 mm.
Fine sand	0.25–0.10 mm.
Very fine sand	0.10–0.05 mm.
Silt	0.05–0.002 mm.
Clay	< .002 mm.

¹ A. Swineford and F. Swineford, A Comparison of Three Sieve Shakers, *Journ. Sed. Petrol.*, **16**, 1946, p. 3.

² *Soil and Plant Analysis* (Interscience Publishers, New York), 1947.

³ Methods of Making Mechanical Analysis of Soils, *Soil Sci.*, **68**, 1949, p. 15.

⁴ *Manual of Sedimentary Petrography* (Appleton-Century-Crofts, New York), 1938.

The grades separated in the soil investigations in Indonesia are based on those of the U.S. Bureau of Soils, but contain more sub-divisions of the silt¹.

Gravel > 2 mm.		mm.
Fraction	1. Very coarse sand	2-1
	2. Coarse sand	1-0.5
	3. Medium sand	0.5-0.2
	4. Fine sand	0.2-0.1
	5. Very fine sand	0.1-0.05
	6. Coarse silt	0.05-0.02
	7. Silt	0.02-0.005
	8. Fine silt	0.005-0.002
	9. Clay	0.002-0.0005
	10. Colloidal clay	< 0.0005

The upper part of the U.S. Bureau of Soils scale has similar grade sizes to that of the Wentworth scale² and even the very fine sand and silt approximates to it, probably within the margin of error caused by mesh tolerances. This means that soil can be examined mechanically as a sedimentary material, and this facilitates interpretation of the results of cumulative curves and other statistical treatments.

In the standard procedure for mechanical analysis, 10 g. is the recommended sample weight³, but it has been found preferable to use samples larger than 10 g. for the pipette method because larger quantities of the products are then obtainable and can be used, as shown in the flow sheet (Ch. III, Table 3, p. 304) for mineralogical, chemical, X-ray and other examinations. Use of an end-over-end shaker facilitates handling of samples up to 100 g. weight.

If figures for a mechanical analysis are not required and the clay is removed from the soil in order to obtain the fine sand for mineralogical examination, either washing out by hand in a large evaporating dish (12-15 in. in diameter), or sedimentation for the correct length of time (according to Stoke's law) in beakers, to give the required grade of material, is satisfactory.

B. Chemical Examination. Chemical analysis may include a partial analysis of the whole soil and of the clay fraction. Modifications of the standard procedures for the analysis of silicate rocks whereby SiO_2 , Al_2O_3 , Fe_2O_3 , FeO , TiO_2 , Na_2O , K_2O , CaO , and

¹ E. C. J. Mohr and F. A. van Baren, *Tropical Soils. A Critical Study of Soil Genesis as Related to Climate, Rock and Vegetation* (Interscience Publishers, New York), 1954, p. 256.

² C. K. Wentworth, A Scale of Grade and Class Terms for Clastic Sediments, *Journ. Geol.*, **30**, 1922, p. 377.

³ C. S. Piper, *op. cit.*, p. 59.

MgO are determined is satisfactory¹. Rapid analysis methods (L. Shapiro and W. W. Brannock)² greatly increase the number of such analyses which can be made by reducing the time required for each.

Other chemical methods have been discussed by C. E. Marshall and C. D. Jeffries³; in addition it is often necessary to remove free iron oxide coatings from grains. One method is by the use of sodium hydrosulphite^{4,5,6} or by nascent hydrogen produced by C. D. Jeffries' method⁷. A discussion of these and other methods is also given by R. J. W. McLaughlin⁸.

The ion-exchange capacity of soils and clays is an important property. Methods based on leaching with neutral ammonium acetate have been used by agricultural chemists for many years⁹. A method which is rather more rapid is that of C. A. Bower and E. Truog¹⁰ in which the exchangeable ions are replaced by manganese which is determined colorimetrically. The exchange capacity can then be read directly from a prepared graph from the readings of a colorimeter or spectrophotometer.

C. Mineralogical Examination. It is standard practice in mineralogical examination of sand and coarse silt fractions of soils to separate minerals of higher from those of lower specific gravity, and as bromoform (S.G. 2.9)¹¹ has commonly been used for this purpose, heavy minerals are those whose S.G.s are greater than that of bromoform. Various liquids which can be used for mineral separation are described in Vol. I, Ch. III. C. E. Marshall and C. D. Jeffries¹² have discussed the technique of heavy liquid separations where a centrifuge is used¹³. Separations are generally made in special separation funnels, but where these are not available, an evaporating dish as described by F. G. Tickell¹⁴ can be used satisfactorily. Either alcohol (95–100%) or acetone may be used to remove excess bromoform from the sample, which can later be recovered.

¹ C. S. Piper, *op. cit.* See also Vol. I, Ch. VIII.

² U.S. Geol. Surv., Bull. 1036-C, 1956.

³ Proc. Amer. Soc. Soil Sci., 10, 1945, p. 397.

⁴ B. C. Deb, Journ. Soil Sci., 1, 1950, p. 212.

⁵ N. H. Aquilera and M. L. Jackson, Amer. Soc. Soil Sci. Proc., 17, 1953, p. 4.

⁶ R. C. Mackenzie, Journ. Soil. Sci., 5, 1954, p. 167.

⁷ Amer. Soc. Soil Sci. Proc., 11, 1946, p. 211.

⁸ Geochim. Cosmochim. Acta, 5, 1954, p. 85.

⁹ W. P. Kelley, Cation Exchange (Reinhold, New York), 1948.

¹⁰ Ind. Eng. Chem. Anal., Ed. 12, 1940, p. 411.

¹¹ Bromoform may have a lower S.G. than 2.9 when it has to be reconditioned by shaking up in water; the bromoform is recovered by means of a separation funnel. A rhomb of calcite is a useful indicator for the correct specific gravity.

¹² *Op. cit.* ¹³ See also Vol. I, Ch. III.

¹⁴ The Examination of Fragmental Rocks, 3rd ed. (Stanford University Press), 1947.

In what may be termed reconnaissance investigations, only one grade of material is separated, fine sand (0.25–0.10 mm.) or very fine sand (0.10–0.05 mm.), but for more rigorous investigations, where time is not a limiting factor, each grade obtained from a mechanical analysis is separated in bromoform and the minerals in both heavy and light fractions identified. Whether one grade or several should be examined has been discussed by J. F. Haseman and C. E. Marshall¹ and C. E. Marshall and C. D. Jeffries², who point out that a somewhat different mineral assemblage is to be expected from different grade sizes. This has been mentioned by many investigators, a good example being that of J. I. S. Zonneveld³; it is an inherent part of most of the German soil and sediment work. Many, however, follow C. H. Edelman's method⁴, which has also been described by D. J. Doeglas⁵ and by E. C. J. Mohr and F. A. van Baren⁶. The advantages of the Edelman method have been evaluated by L. de Leenheer⁷.

For unconsolidated sediments it has been found good practice to consider W. W. Rubey's findings⁸ when deciding which grade of material will be most profitable to examine microscopically. That author pointed out the importance of the equivalent or hydraulic grade of the heavy minerals, which means that smaller sizes of heavy minerals will be transported than of the accompanying quartz and feldspar. Therefore, if a mechanical analysis is available, the material on the fine side of the maximum grade should be separated for heavy minerals. An interesting discussion of the grade sizes to be used is given by B. Brajnikov⁹.

In soil investigations it has been found advantageous to obtain (1) per cent by weight of heavy residue and (2) quantity, if any, of magnetite present. Both help to characterize the mineralogical composition of a soil. For magnetic separation, a small bar magnet or a horseshoe magnet can be used; it may sometimes be necessary to use an electro-magnet, or a Frantz isodynamic separator, if the latter is available.

Identification of mineral grains in both heavy and light fractions can be learnt by utilizing information in Ch. I, which describes diagnostic properties of all mineral grains likely to be found

¹ *Univ. Missouri Coll. Agric. Research Bull.*, 387, 1945.

² *Op. cit.*

³ *Geol. en Mijnb.*, 8, 1946, pp. 83 and 93.

⁴ *Proefscr. Naturk. Univers. Amsterdam*, 1933, p. 104.

⁵ *Rep. Comm. Sedimentation*, U.S. National Research Council, 1939–40.

⁶ *Op. cit.*

⁷ *I.N.E.A.C. Serie Scient.*, 15, 1944; *Trans. 4th Inter. Congr. Soil Sci.*, 2, 1950, p. 84.

⁸ *Journ. Sed. Petrol.*, 3, 1933, p. 3.

⁹ *Bull. Soc. Geol. France*, 14, 1944, p. 381.

in soils. In addition, the student should make for himself or otherwise acquire a set of slides with identified minerals (from soils or sediments), particularly heavy minerals, of which about thirty are commonly found in soils.

In the microscopic examination of mineral grains, determination of refractive index is of considerable importance in identifying the various minerals, particularly for those just beginning such studies. The method of determining refractive indices is given in Vol. I, Ch. VI. There are now available refractive index liquids with indices up to 2.0¹. A very useful technique for identification of mineral grains is given by C. E. Marshall and C. D. Jeffries² who describe preparation of gelatin mounts in which grains are embedded, so that various media can be used on the same grains without their being washed away and lost.

In soil mineralogical investigations, as in other sedimentary petrographical studies, two other aspects of the mineralogy are of importance: variation in composition of heavy residue, generally expressed as a percentage; and identification of any varietal features which may have significance in characterizing the material.

The percentage composition of heavy residue, occasionally of the light fraction, is obtained either by counts or by estimates of frequency, both of which are discussed in Ch. IV. Tabulations of percentage composition by grain count may appear to imply a greater accuracy than is present in actual fact, but if about 300 grains are counted, accuracy is approximately 5%³, sufficient if the method of sampling is also considered. The Dutch school of sedimentary petrologists count opaque separately from non-opaque grains and their method is followed by many other continental investigators^{4,5}.

Varietal features of such minerals as zircon, tourmaline, rutile, amphibole, garnet and many others should be noted when describing heavy mineral assemblages, as such features often enable distinctions to be made between otherwise similar heavy residues. This feature is of particular importance in differentiating assemblages in which there are very few minerals, *e.g.* in soils derived from sedimentary rocks (Ch. IV, p. 385).

Identification of the minerals of the light fraction is of equal importance to that of the heavy residue, particularly where estimation of the mineral reserve of a soil is concerned.

Stability of various minerals in soil environments is not fully

¹ R. Meyrowitz and E. S. Larsen Jr., *Amer. Min.*, **36**, 1951, p. 746.

² *Op. cit.*

³ A. L. Dryden, *Proc. Nat. Acad. Sci.*, **17**, 1931, p. 233; *Amer. Journ. Sci.*, **29**, 1935, p. 393.

⁴ C. H. Edelman, *op. cit.*

⁵ D. J. Doeglas, *op. cit.*

understood. For sediments in general, it has been discussed by F. J. Pettijohn¹ and F. Smithson², among others (see also Ch. VI). Probably the best discussion of mineral stability in soils is that of R. Weyl and Tj. H. Van Andel³. The alteration of mineral grains within the soil is of the very greatest importance in soil fertility problems and examples will be given in later parts of this chapter.

D. Expression of Results. Results of soil mineralogical investigations can be expressed in various ways. Tabulation of figures for results of mechanical analyses and of heavy mineral percentages in samples, gives information which is sometimes not clear; it is advantageous to use graphical methods whenever possible. The arrangement of data in a pictorial form facilitates reading and interpretation of results. An outline of methods available is given by W. C. Krumbein and F. J. Pettijohn⁴.

For mechanical analyses, cumulative frequency curves plotted on a semi-logarithmic basis are satisfactory, while results of analyses by the International Method into sand, silt and clay are often plotted in a triangular co-ordinate graph, which is also used by soil scientists for their soil textural classes.

Bar-charts or histograms of heavy mineral results show differences between samples very readily, as do range-tables such as those used by P. Evans, R. J. Hayman and M. A. Majeed⁵ for mineral variation in oilfield samples. A variation of this method of representation is commonly used by Dutch and other continental workers. Pie-diagrams have been used very effectively by B. Brajnikov⁶ in his study of the Seine sediments.

E. Soil Colour. Colour of a soil is an important property depending on climate and composition. Descriptions of soil-colour have now been standardized in the United States with publication of the Munsell Soil Colour Chart⁷ and its future use will facilitate comparison of soil colours in descriptions of soils from different countries. In order to illustrate the use of this colour chart, some soils recently examined by the author had the following colours:

RESIDUAL MATURE SOIL ON LIMESTONE		RESIDUAL SOIL ON SHALE	
<i>in.</i>	<i>colour</i>	<i>in.</i>	<i>colour</i>
0-10	10 YR 4/3	10-15	10 YR 5/4
10-15	7.5 YR 4/4	23-25	10 YR 6/4
15-21	5 YR 4/6	24-36	10 YR 5/6
21-23	5 YR 4/6		

¹ *Sedimentary Rocks* (Harper, New York), 1949.

² *Science Progress*, **149**, 1950, p. 10.

³ *Erdöl u. Kohle*, **5**, 1952, p. 29. ⁴ *Op. cit.*

⁵ *Proc. World Petrol. Conference*, **1**, 1933, p. 251.

⁶ *Bull. Inst. Ocean Monaco*, **44**, 1947.

⁷ R. L. Pendleton and D. Nickerson, *Soil Sci.*, **71**, 1951, p. 35.

An alluvial soil in which the colour was inherited from the rocks of the area had a colour of 10R 3/2. All these figures are for moist soils.

Red and yellow soil colours are due to presence of iron oxides in one form or another. An interesting discussion on the black colour of soils is given by E. C. J. Mohr and F. A. van Baren¹ and from investigations in India and Africa it appears that the black colour is due to the kind of clay mineral present, generally montmorillonite, also nature of the organic compounds². This refers particularly to black earths in tropical or semi-tropical climates. Accumulation of organic matter as peat does not have the same effect on soils, although the surface soil is black.

Colour of soils and sediments may often be due to the colour of the parent material, *e.g.* purplish shales and red sandstones will, in their finest particles, retain this colour and give it to the weathered product. Often colour is the result of a thin mineral coating on sand grains, *e.g.* hematite on the quartz grains in the Simpson Desert sand, Australia (colour is 10R 4/8).

EXAMPLES OF SOIL MINERALOGICAL STUDIES

One of the important types of soil mineralogical investigation is that concerned with the residual minerals in soils, *i.e.* mineral grains derived from the parent rock and persisting, fresh or altered, in the soil. As minerals have a definite chemical composition, it is advantageous to know which are present, for by their chemical disintegration, and to some extent also by their mechanical disintegration, chemical elements required for the growth of plants will be provided. Not only do certain minerals contain the major chemical elements, such as Mg, Ca, P, K, but they also contain traces of elements like Cu, Co, Ni, Mo, B, and many others important for plant and animal growth. Certain minerals act as 'hosts' to these trace elements and they do so according to well-defined geochemical laws³.

A. Investigations of Residual Minerals of Soil. (1) *Tropical Regions.* Under moist tropical climates the rate of alteration of rock to soil is rapid and all alterable mineral grains coming from the parent rock are eventually removed. This might be thought to result in very similar soils in every locality but, as pointed out by C. E. Kellogg⁴, the differences in soil parentage seem to be emphasized by this intense weathering.

¹ *Op. cit.*, pp. 424-433.

² J. Theron and P. le R. van Niekerk, *S. African Journ Sci.*, **31**, 1934, p. 320.

³ V. M. Goldschmidt, *Soil Sci.*, **60**, 1945, p. 1.

⁴ *Trans. 4th. Inter. Congr. Soil Sci.*, **1**, 1950, p. 266.

There is an extensive literature on tropical soils and on lateritic soils which are an expression of the results of continued leaching in a warm moist climate, whereby silica is removed and alumina and iron accumulate.

Much important research has been done on tropical soils, particularly in Indonesia, Central Africa, Hawaii, India and in the Caribbean region, in connexion with utilization of soils for agriculture.

Many important investigations of the residual minerals in soils have been made by the Dutch in Indonesia during the past forty years. This research has been summarized by E. C. J. Mohr and F. A. van Baren¹ who state that these investigations have involved many thousands of soil samples. The objectives have been 'for purposes of classification, by determining the type of parent material, but also for the estimation of the agricultural value of soon-to-be-reclaimed regions where soil reconnaissance had been carried out'.

Early work in Indonesia was concerned with recognition of volcanic ash minerals in soil profiles and was largely initiated by E. C. J. Mohr². Many examples of differentiation of homogenous and non-homogenous soil profiles are given by E. C. J. Mohr and F. A. van Baren³ and variations in heavy minerals, resulting from different parentage, are shown in Table 8⁴.

TABLE 8

MINERALOGICAL COMPOSITION OF THE HEAVY MINERAL RESIDUE OF SOILS OF DIFFERENT ORIGIN (IN PERCENTAGS OF NON-OPAQUE MINERALS)

LOCALITY	SAMPLE NO.	OPAQUE	TOURMALINE	ZIRCON	GARNET	RTILITE	ANATASE	BROOKITE	SPHENE	STAUROLITE	KYANITE	ANDALUSITE	CHLORITOID	EPIDOTE	GR. HORNBLende	BASALTIC HORNBLende	AUGITE	HYPERSTHENE	GLAUCOPHANE	LAWSONITE	ORIGIN
Residency	16993														1	98	1				Volcanic soils
Jogjakortan	20048	2													94	4	2				
Java	20018														15		85				
Java	20378	13													71	20	8	1			Volcanic mixed with Metamorphic material
Java	22195	84		9	6				4					21	51	1	5	3			
Residency	64973	55	2	84		4						2					1	7			Metamorphic material
Bodjonegoro	64974	63	3	75		2				2		6		5			2	5			
Java	64975	6	6	37		3				8		32		10	4						
Island of Mann, Celebes	60895	55	5	13	2	10	1	1	1	1	3		4	1			1		40	17	Schistose material

¹ *Op. cit.*, pp. 212-254.

² *Bull. Dept. Agric. Indie N'eerl.*, 47, 1911.

³ *Op. cit.*, Ch. VI.

⁴ *Op. cit.*, Table 74, p. 222.

Investigations of lateritic and podzolic soils have been made by H. Kiel and H. Rachmad¹ which show the effect of soil-forming processes on biotite.

TABLE 9

MINERALOGICAL COMPOSITION OF THE SAND FRACTIONS $>50\mu$ OF A LATERITIC AND OF A PODZOLIC SOIL FROM SUMATRA
(After H. Kiel and H. Rachmad, 1948)

A. LATERITIC SOIL.		Minerals in Mutual Percentages																	
HORIZON	DEPTH IN CMS.	OPAQUE	ZIRCON	GR. HORNBLende	HYPERSTHENE	ORTHITE	OLIGOCLASE	SANIDINE	QTZ. TRANS.	QTZ. TURBID	VOLCANIC GLASS	BIOTITE	BIOTITE*	WEATHER PRODUCTS**	WEATHER PRODUCTS***	IRON STAINED FRAGMENTS	SERICITE	ORGANIC SiO ₂ ****	HUMUS
A ₁	0-10	tr	tr	tr			12 31	49	2	2	3					tr	1	tr	
A ₂	10-30	tr	tr				13 31	43	2	3	6					1	1	tr	
A ₃	30-55	tr	tr	tr		tr	10 31	45	3	1	8					1	1	tr	
B ₁	55-120						12 26	38	1	tr	20					1	2		
B ₂	120-270						8 17	26	1	3	42					tr	3		
B ₃	270-500	tr	tr	1			13 21	22	tr	4	37					1	1		
C	500-600	tr	tr	tr			11 12	9	tr	46	22						tr		
B. PODZOLIC SOIL																			
A _r	30-35						10 15	65	tr	10									
B ₁	35-40						17 13	44	tr	6									20
B ₂	40-45			1			17 11	30		16					25				
C	45-75						26 7	19		22		13		13					
D	> 75			2	tr		28 10	24		2	14		20						

* Biotite bleached and weathered to an amorphous residue, crystal habit maintained

** Soft yellowish-white isotropic colloidal material, sometimes with inclusions of fresh minerals, n = ± 1.544.

*** Red-brown, iron-infiltrated, weathered pumice fragments

**** Organic SiO₂ is amorphous silica which is concentrated by the removal of soil solution by plant roots.

Recent studies in the Celebes by F. F. F. E. van Rummelen and W. L. P. L. Monthaan² describe soils of the Sawitto Plain, the parent materials of which are unconsolidated sediments deposited by the Sadang River and its tributaries. A distributive province with seven major rock formations provides a variation in the kind and quantity of heavy minerals found in the soils of the plain. On mineralogical investigation it was found that the

¹ Landbouw (Buitenzorg), 20, 1948, pp. 281, 283.

² Landbouw (Buitenzorg), 25, 1953, p. 131.

plain could be divided into three provinces and two transition zones:

1. Augite province.
 - 1a. Epidote-augite association.
2. Epidote province.
 - 2a. Zircon-epidote association.
3. Zircon province.

In addition to surface samples of the 92 soil types as mapped, a number of profiles were examined and these show the vertical distribution of the different provinces, thus linking this type of investigation with the more familiar stratigraphic studies reported elsewhere¹. In addition, mechanical analyses show the grain-size differences of the materials of the three distributive provinces.

This brief summary of the valuable and comprehensive soil mineralogical investigations made in Indonesia (largely published in Dutch) should be supplemented by reading the account given by E. C. J. Mohr and F. A. van Baren².

In the Belgian Congo, reserves of weatherable minerals have been investigated as a guide to the future agricultural use of certain soils. It is important to know, when estimating quantities of alterable minerals in a soil, whether the profile originates from the rock beneath it, or whether it contains transported materials. As an example of this type of examination, a summary is given of an investigation by L. de Leenheer³ of nine soils. Complete mineralogical details are given of the light and heavy fractions of several grades of material. Separations were made at S.G. 2.63 (separation of potash feldspars from quartz), 2.67 (separation of quartz from basic plagioclases and micas), and S.G. 3.03 (separation of micas, more or less altered, amphibole, tourmaline and other heavy minerals). Grain counts were made for each fraction separated and are summarized⁴ in Table 10.

Soils 11, 12 and 13 contain much zircon and metamorphic minerals in the heavy residues.

From a fertility point of view these soils are classified as:

Mineral reserve nil: Nos. 11, 12, 13.

„ „ small: No. 19.

„ „ good: Nos. 14, 16, 22.

„ „ high: Nos. 17, 23.

¹ D. J. Doeglas, *Afzettingen gesteenten* (Servire's Encyclopaedic, The Hague 1952).

² *Op. cit.*, 1954.

³ *Op. cit.*, 1944.

⁴ L. de Leenheer, *op. cit.*, 1944, Table VIII.

TABLE 10

MINERALOGICAL COMPOSITION OF SAND FRACTIONS $>50\mu$
(After L. de Leenheer, 1944)

Soil No.	11 %	12 %	13 %	14 %	16 %	17 %	19 %	22 %	23 %
Quartz	100	100	100	65.4	62.9	6.9	96.1	74.5	54.6
Orthoclase } Microcline }				15.9	5.2	.6	2.1	15.1	7.8
Alt. biotite				10.0	22.6	52.4		8.0	24.5
Biotite*				.5	1.0	3.2	tr	.8	24.5
Muscovite				4.0	4.2	.5	.5	.5	4.5
Amphibole				.2	1.9	24.6		.1	tr
Plagioclase						8.5			
Opaque				3.1	1.2	.7	1.7	.14	.04
Totals	100	100	100	99.25	99.15	97.57	100.45	99.27	99.81

* Fresh or slightly altered.

tr = trace.

Soil 17 is an example of a young soil with a high mineral reserve. In the mechanical analyses the total fraction above 50μ is 50% to 60% of the soil. Information is also given concerning the fraction up to 10μ which is largely kaolinite. This will be discussed later when considering soil-development studies.

In the Hawaiian Islands many soils derived from basalt (of which the islands are almost entirely composed), have been found to contain an accumulation of iron and titanium minerals in the A_2 horizon^{1,2}. The principal minerals are hematite, ilmenite and anatase. The development of these soils will be discussed in a later part of this chapter.

Soil mineralogical investigations have been made in India by S. P. Raychaudhuri and K. C. Mukerjee³ and by S. P. Raychaudhuri and A. H. Mian⁴ on red and lateritic soils. The mineralogical data have been recalculated by E. C. J. Mohr and F. A. van

¹ G. Fujimoto, G. D. Sherman and A. E. Chang, *Soil Sci. Soc. Amer. Proc.*, **13**, 1948, p. 166.

² G. D. Sherman, Z. C. Foster and G. Fujimoto, *Soil Sci. Soc. Amer. Proc.*, **13**, 1948, p. 471.

³ *Indian Journ. Agric. Sci.*, **12**, 1942, p. 323.

⁴ *Indian Journ. Agric. Sci.*, **14**, 1944, p. 117.

Baren¹; it is shown that the soils can be grouped according to parent material.

An interesting discussion of tropical soils in relation to plant nutrition is given by H. W. van der Marel². The changes in heavy mineral content (mean of ten soil profiles) are related to degree of weathering. His data have been arranged as Fig. 75. Similar changes on weathering in Indonesian soils were reported by G. A. Neeb³.

Although not now tropical soils, there are extensive areas in southern Australia covered with complete or partial remains of lateritic soils^{4,5,6}. Investigations have shown that reserves of weatherable minerals have been completely removed from these soils and that resistant minerals have accumulated. In the extensive sand-plain areas of the Yilgarn gold-field, Western Australia, for example, mineralogical examination showed the origin of these soils to be in granite and metamorphic rocks (Fig. 76)⁷.

(2) *Temperate Regions.* Some interesting investigations of soil mineralogy have been made in Europe. In 1930 J. van Baren published a paper on the differentiation of a limestone and a loess-soil profile in the Limberg region of Holland⁸. This paper is entirely modern in treatment and outlook and contains considerable mineralogical as well as chemical and physical details. Mechanical analyses emphasize grain-size differences.

Following the investigation of the weathering of potash felspar by C. W. Correns and W. von

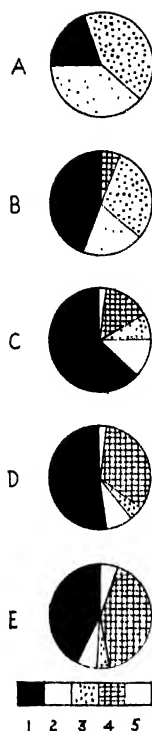


FIG. 75.

Composition of the heavy mineral fraction of soil at varying stages of weathering under tropical conditions (after H. W. van der Marel, 1947).

- A-Very strongly weathered;
- B-strongly weathered
- C-Medium weathered
- D-Slightly weathered
- E-Rhyolitic tuff
- 1-Opaque minerals
- 2-Zircon
- 3-Allanite
- 4-Amphibole
- 5-Hypersthene.

¹ *Op. cit.*, 1954, pp. 205-251.

² *Soil Sci.*, **64**, 1947, p. 445.

³ *Verh. 7de Ned. Ind. Natuurwetenschappelijk Congres*, Bateria, 1936, p. 695.

⁴ J. A. Prescott, *Austral. Council for Sci., and Ind. Res. Bull.*, **52**, 1931.

⁵ C. G. Stephens, *Austral. Council for Sci. and Ind. Res. Bull.*, **206**, 1946.

⁶ D. Carroll, *Austral. Journ. Sci.*, **14**, 1951, p. 41.

⁷ D. Carroll, *Geol. Surv. West Austral. Bull.*, **97**, 1939, App.

⁸ *Meded. Landb. Wageningen*, **34**, 7, 1930.

Engelhardt¹, in which mechanism for alteration of feldspar was found experimentally, W. von Engelhardt² described the breakdown of the feldspars and the formation of aluminous and iron minerals in three profiles of Bleicherdwaldboden. In the ortstein layer of these sandy soils he found large quantities of amorphous aluminium trihydrate together with iron oxide and phosphoric acid.

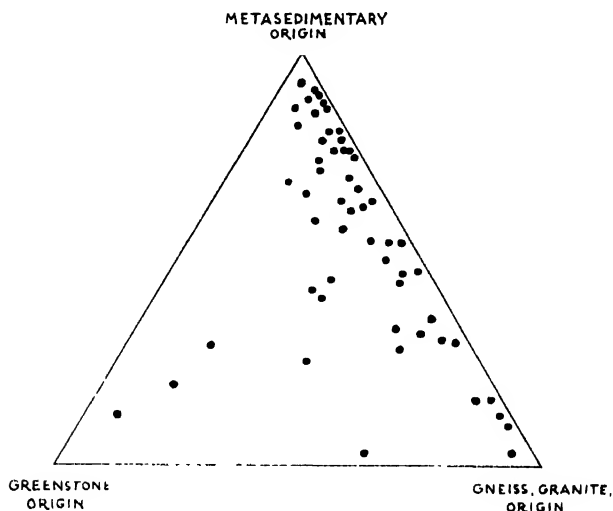


FIG. 76. Parentage of sandy soils in the Yilgarn Goldfield, Western Australia, as shown by the percentage composition of the non-opaque heavy mineral assemblages. The diagnostic minerals for the three groups are:

Metasedimentary origin: andalusite, kyanite, staurolite, sillimanite and spinel.

Gneissic and granitic origin: zircon, tourmaline, garnet, sphene, rutile.

Greenstone origin: amphiboles, epidote, zoisite. (After D. Carroll, 1939.)

The amount of fresh and altered feldspar at different soil horizons is given in Fig. 77. C. W. Correns and F. K. Schlunz³ described in detail three other Mecklenburg soil-profiles and showed the variations in quantities of quartz, feldspar, mica and clay minerals.

In the vicinity of the Werra river near Hannovermündel, Germany, C. H. Edelman⁴ examined soils developed above the Buntsandstein, the 'Muschelkalk, and basalt, and from their mineralogy was able to determine the amount of mixing of parent

¹ *Chemie der Erde*, 12, 1938, p. 1.

² *Chemie der Erde*, 13, 1940-1, p. 1.

³ *Zeit. Pflanzenernährung, Düngung und Bodenkunde*, 44, 1936, p. 316.

⁴ *Meded. Landb. Wageningen*, 40, 1936, p. 3.

material and loess. This appears to be the first application of this particular method to European soils, although it had been used by the Dutch in Java for many years. In this general area also, complete studies have recently been made of five soil profiles by H. Huffman¹. Details of the minerals present in a sample of soil at 0.1 m. in a profile on olivine basalt at Brunsberg are as follows:

TABLE 11

Fraction Minerals	2000-200 μ %	200-63 μ %	63-20 μ %	20-6 μ %	6-2 μ %
Brown aggregates } Rock particles }	57	26 37.8	22.7 10.0	34.7 2.8	50.5 —
Dark brown olivine residue	—	0.2	2.0	—	—
Augite	18.3	10.7	21.5	8.5	12.7
Magnetite	16.1	8.6	6.0	6.5	12.0
Quartz	6.1	11.0	22.5	5.5	2.8
Alkali-felspar	—	0.7	10.3	26.2	4.7
Biotite	2.5	2.9	2.5	3.5	12.0
Volcanic glass	—	1.4	1.5	—	—
Organic SiO ₂	—	—	1.0	12.3	5.3

Much information is also given on the clay minerals.

Comprehensive studies of weathering and soil-formation on alluvial terraces in Germany have been made by M. Salger², but as these are principally concerned with the clay minerals, no further mention of this work is made here.

H. W. van der Marel³, in a detailed mineralogical examination of a heath podzol profile in the Netherlands, gives much information concerning weathering and removal of heavy minerals and his Table 2 shows loss of epidote, saussurite and amphibole from the surface horizon. In addition, the appearance of the weathered minerals is given in photomicrographs. He, too, records aluminous material in this profile similar to that found by W. von Engelhardt⁴ and suggests that it may be comparable in origin to the diaspore in old lateritic soils reported by D. Carroll and N. K. Jones⁵. He stresses the activity of podzolic weathering in removing certain minerals.

¹ *Heidel. Beit.*, **4**, 1954, p. 67.

² *Heidel. Beit.*, **4**, 1954, p. 288.

³ *Soil Sci.*, **67**, 1949, p. 193.

⁴ *Op. cit.*, 1940-41.

⁵ *Soil Sci.*, **64**, 1947, p. 1.

The variation in fertility of certain Belgian soils has been described by L. de Leenheer¹ as due to the percentage of feldspar in the sand fractions. He made profile studies of the soils in several areas with the following results:

TABLE 12
DISTRIBUTION OF POTASH FELSPARS IN CERTAIN BELGIAN SOILS
(After L. de Leenheer, 1949)

	Depth in cm.	Sand > 50 μ	K Feldspars %	Other Minerals (omitting quartz) %
Region limoneuse Waterloo	0-27	25.8	7	6 (4% biotite)
	27-66	11.5	7	4 (3% opaques)
	66-150	17.9	8	4 (biotite)
Region sablonneuse Flammande Eccloo	0-24	87.5	16	2 (opaques)
	24-75	92.5	12	2 (")
	75-109	97.2	15	1 (")
	109-124	97.5	15	1 (")
	124-150	85.0	15	
Region poldérienne (a) heavy clay soil Lampernisse (sols de cuvette) (b) sols des chenaux (channel), Alveringham Eggwaarts- Kapelle	0-5	20.9	14	1 (glauconite)
	5-14	19.4	17	4 (various)
	64-95	39.9	25	4 (biotite)
	95-106	55.6	17	5 (")
	106-150	74.5	25	2 (")
	86-107	73.9	19	4 (")
	107-121	63.6	20	2 (")
	121-150	86.8	45	2 (")

The value of a mineralogical examination of sand fractions of soils as an aid to interpreting the contribution of the underlying rocks and of transported material, is shown by F. Smithson² for North Wales soils. After a comprehensive investigation of the mineralogy of the country rocks, he found that only in very few instances was there no contamination with material of Pleistocene glacial origin. Much mineralogical detail is given in his paper.

A mineralogical study of two high altitude soils from Trollheimen, Norway, by H. Høltedahl³ gives interesting information concerning distribution of various minerals in the profiles and the

¹ 4th. Inter. Cong. Soil Sci. Trans. 11, 1950, p. 1; Bull. Soc. Belge biol. Palaeon. Hydrol., 58, 1949, p. 208.

² Journ. Soil Sci., 4, 1953, p. 194.

³ Norsk Geol. Tidsskr., 32, 1953, p. 191

quantity of heavy residue. These soils, derived from gneisses and schists, show no chemical weathering.

A discussion which summarizes all recent work on the stability of minerals in soils and sediments, is that of R. Weyl and Tj. van Andel¹. Much detail is given of the etching of mineral grains and their disappearance in various environments.

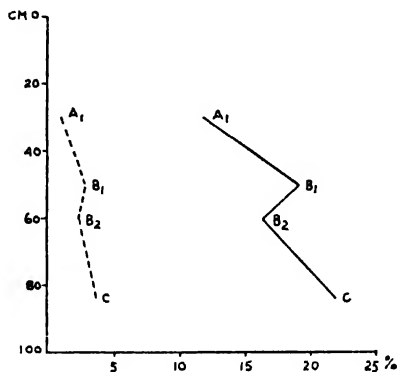


FIG. 77. Variation in percentage of fresh (solid line) and altered feldspar (broken line) at different soil horizons in a profile developed in dune sand (after W. von Engelhardt, 1940).

In the United States, the value of mineralogical examination of soils was recognized in the work of W. H. Fry², which later resulted in a bulletin describing petrographic methods for soil laboratories³. The principal soil mineralogical work has been closely tied to geology, and investigation of the clay minerals has proceeded at the same time (see Ch. III). It is not possible here to mention all investigations pertaining to residual minerals of soils, but it is believed that the bibliography (p. 505) is reasonably complete to 1955.

J. F. Haseman and C. E. Marshall⁴ have summarized the use which can be made of heavy minerals in studies of origin and development of soils. In seeking a mineral which could serve as an indicator for changes taking place during soil formation (profile development), zircon is suggested, and an example of its use is given for a Grundy silt-loam profile.

Important studies have been made by E. R. Graham⁵ of resistance of plagioclase feldspars to weathering. He found that albite

¹ *Erdöl u. Kohle*, **5**, 1952, pp. 29, 100.

² *Journ. Ind. Eng. Chem.*, **5**, 1913, p. 30.

³ W. H. Fry, *U.S. Dept. Agric. Tech. Bull.*, **344**, 1933.

⁴ *Op. cit.*, 1945.

⁵ *Proc. Amer. Soc. Soil Sci.*, **14**, 1949, p. 300.

is most and anorthite least resistant, and suggests that where sand and silt fractions contain plagioclase, determination of the Ca to Na ratio could be used as a measure of the stage of weathering. The original quantities of feldspar present in the parent rock would have to be determined, however, before this method would give valid results.

The quantities of minerals present in sand fractions of soils have been investigated by C. D. Jeffries¹. He has been particularly interested in the feldspar content and has given detailed analyses of the amount of this mineral in the various horizons of a number of soil types. Of interest too are his figures for quantities of minerals present in the very fine sand fraction (0.10-0.05 mm.) of the ploughed layer of certain soils².

TABLE 13
AMOUNTS OF MINERALS PRESENT PER ACRE PLOUGHED
LAYER IN VERY FINE SAND OF FIVE SOILS

Lb. per acre of minerals in very fine sand separates					
Minerals	Lacka- wanna Loam Sandy	Hagers- town Silt Loam	Volusia Clay Loam	Dekalb A Sand	Dekalb B Clay Loam
Quartz	361,549	243,842	383,130	189,001	479,902
Feldspars	2,264	38,666	36,004	21,536	5,034
Zircon	761	679	1,837	478	1,683
Tourmaline	788	329	1,033	173	228
Muscovite	2,215	391	1,346	386	114
Iron Oxide	6,902	1,816	2,685	1,025	2,523
Chlorite	2,174	214	1,405	—	47
Hornblende	761	140	93	—	52
Rutile	—	—	—	—	90

Other soil mineralogical examinations which have been made include two groups of podzolic soils in Michigan by R. P. Metalski and L. M. Turk³, in which the heavy mineral content was found to be greatest in the C and least in the B horizons, and in which weathering processes appear to have removed much of the original content of opaque and ferromagnesian minerals. This same depletion of weatherable heavy minerals was found also in soils developed on loess in Nebraska⁴. In the latter investigation the authors

¹ *Soil Sci.*, **43**, 1937, p. 357.

² *Op. cit.*, 1937.

³ *Soil Sci.*, **64**, 1947, p. 469.

⁴ J. Adams and R. P. Metalski, *Soil Sci.*, **79**, 1955, p. 59.

followed J. F. Haseman and C. E. Marshall¹ in using variation in quantity of stable heavy minerals, zircon and tourmaline, to calculate depth of soil, total weight of soil, clay content, and green hornblende content of each horizon. The zone of most intense weathering was found to be the lower A₂ and upper B₂ (15-34-in. depth).

Soils developed from loess with an admixture of volcanic ash in south-eastern Washington have been described by F. B. Lotspeich and H. W. Smith². The volcanic material is recognized mineralogically by the presence of pumicite (ash or glass) and hypersthene; the relative proportions of quartz, feldspar, and pumicite, and of the various heavy minerals, are given in a series of histograms. Heavy minerals constitute 2-5% of the very fine sand fractions. It was found that the admixture of volcanic material varied somewhat with topographic position of the soils in this area.

In Australia a number of soil mineralogical studies have been made particularly for identification of soil with parent material. Three distinctive mineral suites were identified in the soils of the Western Australian goldfields³.

The basaltic soils of the state of Victoria were examined mineralogically by A. Nicholls⁴ with the results given in Table 14.

TABLE 14
AVERAGE PERCENTAGE VOLUME OF MINERALS IN THE
FINE SAND OF CERTAIN SOILS ASSOCIATED WITH BASALT

	Brown Loam	Black Clay	Mature Soil
Rock fragments	7.6	.3	tr.
Augite	12.3	1.0	tr.
Plagioclase	19.3	8.7	3.9
Olivine	2.2	.8	.5
Iron oxide	8.4	1.7	1.2
Quartz	50.3	86.8	93.7

The brown soil is from the slope of a basaltic 'stony rise', which passes into a black calcareous clay at the foot of the slope, while the mature soil developed in the surrounding basaltic plains is a grey loam. Quartz is considered an admixture of material from Quarternary deposits on which podzolic soils have developed.

¹ *Op. cit.*, 1945.

² *Soil Sci.*, 76, 1953, p. 467.

³ D. Carroll, *Journ. Roy. Soc. W. Austral.*, 23, 1936-37, p. 7; *op. cit.*, 1939.

⁴ *Journ. Austral. Inst. Agric. Sci.*, 5, 1939, p. 218.

This investigation also shows how the reserve of minerals such as augite, olivine and plagioclase may be removed during the maturing of soils.

The residual minerals in soils as indicators of parent rock, hence of the presence of certain minor elements essential to animal growth, were studied by D. Carroll in Western Australia¹ and in Southern Australia by E. R. Graham². Both copper-deficient and cobalt-deficient soils of sedentary or autochthonous origin are fairly widespread in the agriculturally important south-western part of Western Australia. It had been known for some years that in the goldfields, owing to the lack of relief and drainage, different rocks gave rise to recognizably different kinds of soil. If the parent rock is deficient in any chemical element necessary for animal growth, e.g. copper or cobalt, such a deficiency will be passed on to the soil. In one investigation³, where the copper status of clover (*T. subterraneum*) growing on a number of soils was known⁴, soil

TABLE 15
MINERALOGY OF SOILS AND COPPER STATUS OF
CLOVER GROWING THEREON

Ferro-magnesian mineral content of heavy residue	Copper status of clover samples (<i>T. subterraneum</i>)				
	Rich, over 15 ppm.	High normal, 7.5-15 ppm.	Low normal, 4.6-7.5 ppm.	Sub-normal 3-4.5 ppm.	Deficient
Percentage	No. of Samples	No. of Samples	No. of Samples	No. of Samples	No. of Samples
90-100	12	5	—	—	—
75-90	3	—	—	—	—
45-75	1	—	—	—	—
35-44	1	2	1	—	—
14-43	2	4	1	—	—
7-13	1	—	2	1	1
4-6	1	—	1	—	1
2-3	—	1	1	—	1
0	1	1	4	—	4
Total	22	13	10	1	7

¹ *Journ. Dept. Agric. W. Austral.*, 21, 1944, p. 83; *Soil Sci.*, 60, 1945, p. 413.

² *Soil Sci.*, 75, 1953, p. 333.

³ D. Carroll, *op. cit.*, 1944.

⁴ L. J. H. Teakle and A. C. Turton, *Journ. Dept. Agric. West. Austral.*, 20, 1943, p. 238.

samples to a depth of 6 in. were collected from the same spot as clover samples and an examination made of the heavy minerals. It was found that there was a considerable variation in the quantity of weatherable heavy minerals able to supply the required trace elements present (amphibole, epidote, and biotite). The results are given in Table 15.

The quantity of heavy residue was determined in the sand fraction (0.20–0.14 mm.) and percentage mineral composition by grain counts. The heavy residue for the 'rich' soils ranged from 1% to 69%, and the deficient soils averaged about $\frac{1}{2}$ % by weight of the fine sand fraction.

In another investigation it was found that there was a close relationship between parent rock and cobalt status in the Denmark area (S.W. Australia). A mineralogical examination¹ showed a difference between soil-types, as mapped, which caused cobalt deficiency in cattle and sheep, and those which did not; in addition, such examination explained some anomalies arising from mapping of soils which appeared similar in the field but which had different parentage. The results are given in Fig. 78. It should be noted that the quantity of heavy residue, percentage of which is given as a black line in the diagram, varies considerably. The diagram clearly indicates where mixing of soil types has occurred, and also that a great many of the soils are autochthonous. For the soils which he examined in connexion with this same problem in southern Australia, E. R. Graham² found that the reserve of weatherable minerals was negligible.

In an investigation of the mixing of soil types on a slope, R. Brewer³ examined an area with two very dissimilar rocks, a basalt and a sandstone. The quantity of heavy minerals in six soil samples taken down-slope at known heights and distances from the highest point was obtained, and percentage composition found by counting. The results have been simplified from that author's original diagram (Fig. 79), from which it will be seen that both quantity and species of heavy minerals in the sand fraction are of importance. Another feature described here is the increase in amount of heavy residue in the surface-soils, a fact which has been noted from other localities. It represents the accumulation of resistant mineral grains as a result of the removal of more soluble material by leaching.

In the Upper Hunter River Valley of New South Wales, identification and quantitative estimation of the residual minerals in the

¹ D. Carroll, *Soil Sci.*, **61**, 1945, p. 413.

² *Op. cit.* 1953,

³ *Journ and Proc. Roy. Soc. N.S. Wales*, **82**, 1950, p. 272.

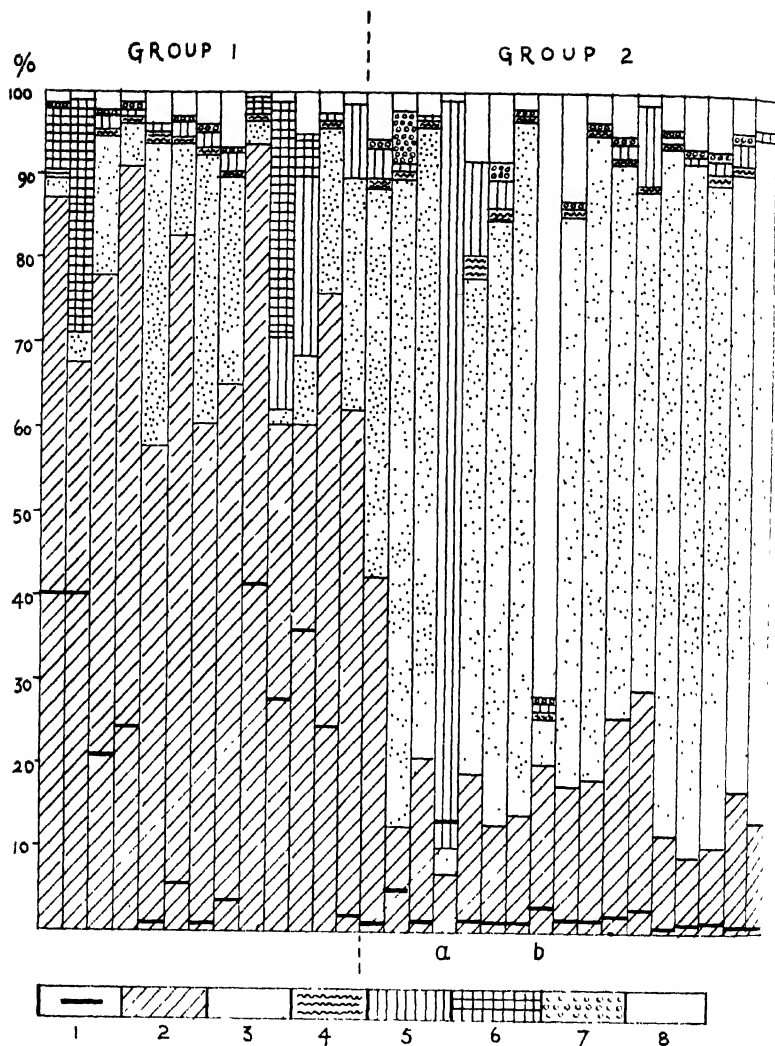


FIG. 78. Mineralogical composition of non-magnetic heavy residues of the fine sand-fraction of soils in an agricultural area which is cobalt deficient (Denmark, Western Australia, after D. Carroll, 1945).

Group 1. Soils which are not cobalt deficient.

Group 2. Cobalt deficient soils.

1. Percentage of heavy residue in the fine sand-fraction;
 2. Opaque minerals (ilmenite, etc.);
 3. Zircon;
 4. Tourmaline;
 5. Amphibole, epidote, zoisite;
 6. Augite;
 7. Garnet;
 8. Other minerals
- (a) Soil residual on amphibole schist.
(b) Soil residual on sillimanite schist.

soils were found to be of assistance in the description of these soils¹.

A reconnaissance type of soil mineralogical investigation was made in 1949, 1950 and 1951 by students in the School of Agriculture, Sydney University, and concerned soils in the arid far western section of New South Wales. It was possible to infer from the mineralogy certain facts concerning the origin of these soils².

WEATHERING AND SOIL DEVELOPMENT STUDIES

There has been a number of investigations of weathering and soil profile development studies in various climates, in which the object has been to arrive at an understanding of mineralogical changes which have taken place; these investigations, therefore, include all minerals in the soil and are not confined to identification of residual minerals of sand fractions. The clay minerals and their identification and quantitative estimation assume great importance here.

The clay minerals will only be mentioned as part of the soil profiles described; their identification and their quantitative estimation have already been given in Ch. III, together with information concerning their genesis in certain environments.

In 1934 the late J. B. Harrison's mineralogical and chemical investigations of the weathering processes of igneous rocks in the humid tropics was published³; it will long remain the classical example of what can be learned of rock weathering by chemical analyses and examination of thin sections of rocks. From such chemical analyses the normative compositions for weathered rocks and soils can be calculated in the same manner as for igneous rocks⁴. The norm minerals used are: kaolinite, gibbsite, quartz, ilmenite, magnetite, and iron oxides (indefinite composition). A number of examples of these calculations are given by E. C. J. Mohr and F. A. van Baren⁵ and they were also used by D. Carroll and N. K. Jones⁶ and D. Carroll and M. Woof⁷. Such normative calculations are very satisfactory when kaolinite is the principal clay mineral present, but X-ray analysis has shown that the clay mineralogy of soils is often complex, and the method cannot be

¹ R. Brewer and B. E. Butler, *C.S.I.R.O. (Austral.) Soil Publ.*, **2**, 1953.

² D. Carroll, *Journ. Sed. Pet.*, **22**, 1952, p. 153.

³ The Katamorphism of Igneous Rocks under Humid Tropical Conditions, *Imp. Bur. Soil. Sci.*, Harpenden, 1934.

⁴ A. Holmes, *Petrographic Methods* (Murby, London), 1923.

⁵ *Op. cit.*, 1954, pp. 137-144.

⁶ *Op. cit.*, 1947.

⁷ *Soil Sci.*, **72**, 1951, p. 87.

used for any useful purpose when it is known that chlorite, vermiculite, hydrous mica, montmorillonite, or mixed-layer minerals are present.

Other calculations can be made from chemical analyses of soil materials; they are concerned with the chemical elements which are lost from the parent rock or added to the soil profile. One such calculation was made by H. G. Raggatt, H. B. Owen and E. S. Hills¹ in which it was shown that only water was necessary in the

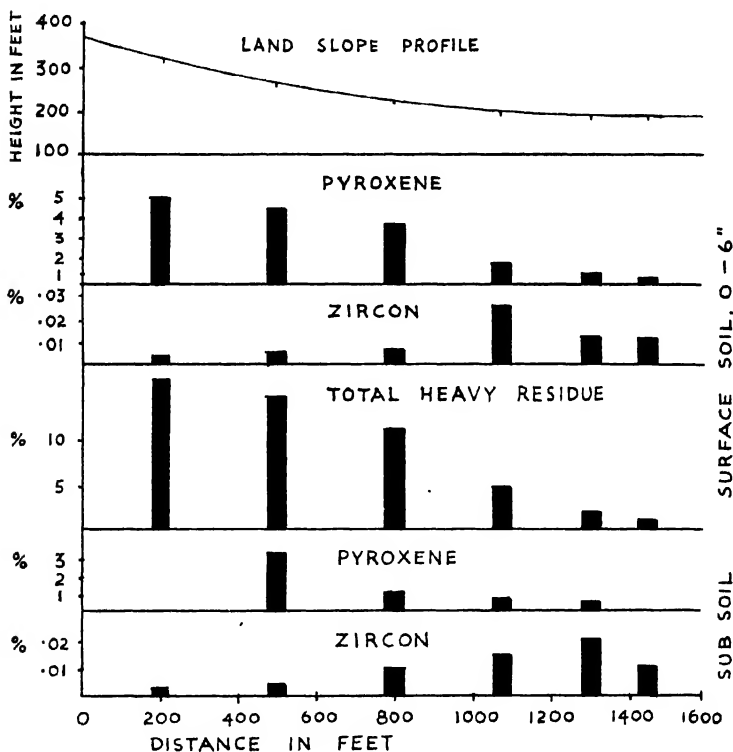


FIG. 79. Variation in total heavy residue, pyroxene and zircon in the fine sand-fraction of soils and sub-soils on a sloping land surface at Prospect Hill, New South Wales, Australia (after R. Brewer, 1950). Parent rock at the top of the slope is basalt; that towards the base is sandstone, which becomes the soil parent material somewhere between 800 and 1,000 feet distance from the highest point shown.

¹ Commonwealth Austral. Dept. Supply Shipping, Min. Res. Bull., 14, 1945, p. 52.

formation of bauxite from basaltic material, while Ca, Mg, Na and K were removed. This is given in Table 16.

TABLE 16
COMPOSITION OF BAUXITE CALCULATED FROM
COMPOSITION OF BASALT
(After H. G. Raggatt *et al.*, 1945)

	Basalt (Aver. 7) (water- free)	Presumed losses from Basalt	Remain- der (in bauxite)	Remain- der recalcu- lated to 100%	Average bauxite	Average bauxite (water- free)
SiO ₂	47.7	45.7	2.0	8.5	5.5	7.8
Al ₂ O ₃	16.1	—	16.1	68.5	52.1	72.2
Fe ₂ O ₃	4.4	9.0	3.0	12.8	7.4	10.5
FeO (as Fe ₂ O ₃)	7.6					
MgO	8.3	8.3	—	—	—	—
CaO	9.1	9.1	—	—	—	—
Na ₂ O	3.0	3.0	—	—	—	—
K ₂ O	1.4	1.4	—	—	—	—
TiO ₂	2.4	—	2.4	10.2	5.3	7.5
H ₂ O	—	—	—	—	29.7	—

A similar agreement in composition was found by D. Carroll and M. Woolf¹ for laterite developed above basalt in New South Wales; in this investigation the weighted average composition for each soil horizon was used, following the procedure of G. J. Hough, P. L. Gile and Z. C. Foster² for Hawaiian soils.

(1) *Soils in Tropical Regions.* In humid tropical weathering, as discussed in Ch. III, changes in original rock minerals are caused by intense leaching in a warm temperature (*circa* 30°C.). All the alterable minerals, feldspars, amphiboles, pyroxenes, micas, etc., are converted into clay minerals of one kind or another, but principally into kaolinite and, if silica is completely removed, into gibbsite or other hydrated aluminium oxides. Research carried out on weathering of rocks and soil formation in the tropics has been summarized by E. C. J. Mohr and F. A. van Baren³. A large number of investigations has been concerned with laterites and lateritic soils; for a discussion of such soils the reader is referred to J. A.

¹ *Op. cit.*, 1951.

² *U.S. Dept. Agric., Tech. Bull.*, 752, 1941.

³ *Op. cit.*, 1954, Ch. IV.

Prescott and R. L. Pendleton¹. A complete bibliography of lateritic soils is given in 'Soils and Fertilizers'².

Although not now strictly tropical soils, fossil laterites and lateritic soils of Australia deserve some mention here. A few detailed studies have been made by H. G. Raggatt, H. B. Owen and E. S. Hills³, F. N. Hanlon⁴, D. Carroll and N. K. Jones⁵, S. E. Terrill⁶ and D. Carroll and M. Woof⁷. These all aim at interpreting development of the laterite profile from parent rocks; chemical and mineralogical data are given.

The Antrim laterites and bauxites of Northern Ireland have recently been re-described by V. A. Eyles⁸. Data given are chemical analyses and determination of minerals by X-ray diffraction, but unfortunately no descriptions of thin sections are given. The parent materials of these bauxites are basalts and rhyolitic sediments and there is considerable discussion concerning the paragenesis of the various minerals, particularly the aluminium oxides. Boehmite and gibbsite, as well as kaolinite, are present; among the iron minerals, maghemite (magnetic $\gamma\text{Fe}_2\text{O}_3$), which has considerable value as an indicator of environment⁹, is recorded. This mineral appears often to be associated with lateritic weathering¹⁰; it was found in the lower part of the lateritic profile examined by D. Carroll and M. Woof¹¹ from New South Wales. In the Belgian Congo lateritic soils have been studied by G. Wagemans¹² in considerable detail.

A comparative study of two profiles, a black earth and a grey earth, derived respectively from hornblende-garnet gneiss and quartz-felspar schist, from near Accra, Gold Coast, was made by I. Stephen¹³, who found that there were very considerable differences in the mineralogy of the A and C horizons. Felspar, hornblende and pyroxene were largely removed by the weathering processes, whereas epidote and garnet accumulated. The clay minerals are kaolinite and montmorillonite in the schist soil (grey earth) and montmorillonite in the gneiss soil (black earth). The rainfall in this area is 25–30 in. and generally occurs during early

¹ *Commonwealth Bur. Soil Sci., Tech. Commun.*, **47**, 1952.

² *Commonwealth Bur. Soil. Sci.*, 1954.

³ *Op. cit.*, 1945.

⁴ *Journ. Proc. Roy. Soc. N.S. Wales*, **78**, 1945, p. 94.

⁵ *Op. cit.*, 1947.

⁶ *Journ. W. Austral. Roy. Soc.*, **34**, 1950, p. 105.

⁷ *Op. cit.*, 1951.

⁸ *Mem. Geol. Surv. N. Ireland*, 1952.

⁹ A. F. Frederickson, *Amer. Inst. Min. Metall. Eng.*, 1952, p. 5.

¹⁰ B. Mason, *Geologiska Foreningens*, **45**, 1943, p. 97.

¹¹ *Op. cit.*, 1951.

¹² *I.N.E.A.C. Ser. Sci.*, **60**, 1954.

¹³ *Journ. Soil Sci.*, **4**, 1953, p. 211.

summer, so that these soils have not developed in a humid tropical climate; leaching is at a minimum and calcium carbonate accumulates in the sub-soil.

The soils of Hawaii have been investigated in considerable detail; many chemical analyses are available, *e.g.* those of G. J. Hough *et al.*¹, who point out the significance of the accumulation of titanium as the result of soil forming processes. Further work by G. D. Sherman and his associates² have identified the titanium-bearing mineral as anatase together with some ilmenite. The clay minerals of these soils have been described by L. A. Dean³ and the chemical composition of the colloid fraction by T. Tanada⁴. Study of the mineralogy and clay fractions has shown that there is considerable variation due to soil forming processes in different environments.

There has been a number of detailed descriptions of soil-profiles from the Caribbean region following the pioneer work of J. B. Harrison⁵. In 1939 A. J. Bonnet⁶ gave a description of a lateritic soil developed from andesitic tuff in Puerto Rico; he stresses the importance of the pH values in different parts of the 20-foot profile studied in the development of laterite and the secondary minerals formed. F. Hardy and G. Rodrigues⁷ examined several profiles of red soils developed from basic igneous rocks; their data include chemical and mineralogical analyses. In a later paper⁸ they describe soil formed from a sedimentary clay in Trinidad. In this profile, the original clay minerals of the parent rock, kaolinite and illite with a little montmorillonite, have been only slightly altered by soil-forming processes.

It is to be noted that there are few descriptions of soils derived from sedimentary rocks in the Tropics. Limestone soils in Java were described by J. van Baren,⁹ but at that time it was not possible to determine the clay minerals with certainty. The change of fresh volcanic ash to soil in Java has also been studied, but details will be given in a later part of this chapter.

(2) *Soils of Temperate Regions.* There is much interesting information available about weathering and soil formation in the temperate regions, but space does not permit more here than to note a few of the studies which have been made.

¹ G. J. Hough and H. G. Byers, *U.S. Dept. Agric. Tech. Bull.*, **584**, 1937; G. J. Hough, P. L. Gile and Z. C. Foster, *op. cit.*, 1941.

² *Proc. Amer. Soc. Soil Sci.*, **16**, 1952, p. 15.

³ *Soil Sci.*, **63**, 1947, p. 95.

⁴ *Journ. Soil Sci.*, **3**, 1951, p. 83.

⁵ *Op. cit.*, 1934. ⁶ *Soil Sci.*, **48**, 1939, p. 25.

⁷ *Soil Sci.*, **48**, 1939, p. 361.

⁸ *Soil Sci.*, **64**, 1947, p. 127.

⁹ *Proc. Pap. 1st. Inter. Cong. Soil Sci.*, **4**, 1927, p. 173.

C. E. Marshall and his students¹ made a number of detailed profile studies of soils on granite and gabbro in Missouri and described the mineralogical changes which took place. They also described the Putnam silt loam² developed from shallow loess overlying glacial drift, and have given a mineralogical description of gumbotil³.

A thorough study has been made of the processes of weathering in North Carolina by J. G. Cady⁴. In the two profiles described, on diorite and meta-gabbro respectively, the first weathering products of the diorite were gibbsite, chlorite and allophane; that of the meta-gabbro was halloysite which formed from the feldspars before the ferro-magnesian minerals were altered. The changes throughout the two profiles were followed by thin sections of the weathered rock, by X-ray and differential thermal analyses, as well as by identification of mineral grains in the sand fractions. Another study of a soil-profile, Davidson clay-loam, was made from the same area by F. Hardy and G. Rodrigues⁵, as part of their study of red soils.

For another type of soil, the Montalto, D. Carroll⁶ described in detail the mineralogical changes which took place during soil formation and was able to show that the profile examined had apparently developed in two stages, possibly separated by a time interval. The first weathering is thought to be due to conditions which induced lateritization and later weathering is of podzolic character in a milder climate. Variations in the heavy minerals are shown in Fig. 80. Other studies include a series on Brown Forest soils by S. B. McCaleb⁷ in which an examination of the minerals is used to indicate the course of weathering and soil development.

In Great Britain a number of important investigations of the change between rock and soil have been made by I. Stephen⁸ working on igneous and metamorphic rocks of the Malvern Hills, where four types of rock and their soils were examined: biotitite, granite, appinite and diorite. He found that the coarser material in the sand fractions contained largely unweathered minerals of the parent rocks; the primary minerals gave rise to distinct types of clay minerals, the biotite-rich and hornblende-rich rocks producing chlorite-vermiculite, whereas increase in the feldspar content caused development of illite, and this is predominant in the soil derived from granite.

¹ *Univ. Missouri Coll. Agric. Res. Bull.*, **359**, 1943.

² *Univ. Missouri Coll. Agric. Res. Bull.*, **386**, 1944.

³ *Soil Sci. Soc. Amer. Proc.*, **14**, 1950, p. 311.

⁴ *Proc. Amer. Soc. Soil Sci.*, **15**, 1950, p. 337.

⁵ *Soil Sci.*, **48**, 1939, p. 483.

⁶ *Soil Sci.*, **75**, 1953, p. 87.

⁷ *Soil Sci.*, **77**, 1954, p. 319.

⁸ *Journ. Soil Sci.*, **3**, 1952, pp. 20, 219.

One of the most detailed studies of rock-weathering and soil formation is that by J. R. Butler¹ of the Lizard area, Cornwall. Chemical and spectrographic analyses are given of five rocks, ranging from granite to serpentine, and of their weathering products. From the data certain deductions can be made concerning distribution of minor elements; for instance, the ratio Fe^{2+}/Co

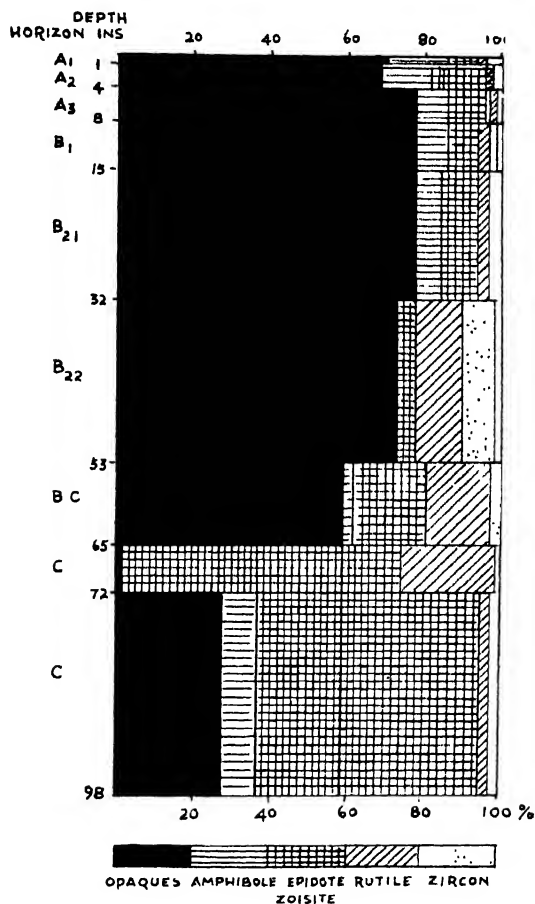


FIG. 80. Mineralogical composition of the very fine sand-fractions of various horizons in a soil developed on metagabbro at Bel Air, Maryland, U.S.A. The soil is a Montalto type which shows mineralogical evidence of two stages of development (after D. Carroll, 1953).

¹ *Geochim. et Cosmochim. Acta*, 4, 1953, p. 157.

decreases on weathering due to retention of Co in the clays. Kaolinite and illite occur in all the clays, and vermiculite is found in those from the granite, granodiorite-gneiss, and hornblende schist. Montmorillonite and talc only occur in the weathering product of serpentinite. The probable change in type of clay mineral from the rock minerals is described, *e.g.* biotite from the granodiorite-gneiss weathers first to chlorite and then to vermiculite in the clay fraction.

Comprehensive studies of soils developed in siliceous rocks (shales, etc.) in Spain have been made by J. M. Albareda *et al.*¹ and as a first stage of this investigation shales were examined and chemical composition, minerals present and exchange capacity determined. The clay minerals were determined by differential thermal analysis and X-ray studies. There is much activity in Spain in the identification of clay minerals and in examination of their distribution.

Comprehensive investigations of recent and fossil weathering of many kinds of rocks in Germany have been made by E. Blanck and R. Melville². A great many chemical analyses are available of weathering products of granites, gneisses, porphyries and sandstones, etc. The work of W. von Engelhardt³, C. W. Correns and F. K. Schlünz⁴ has been discussed earlier in this chapter (p. 474) and as it deals more particularly with mineral residues, will not be further mentioned here. Recent work includes a study of development of soils formed on basalt by H. Huffman⁵ and by P. Schat-chabel and D. Schroeder⁶.

There have been few detailed investigations of soil profiles in the temperate parts of Australia, apart from those mentioned in descriptions of lateritic soils, but a number of mineralogical observations accompanied by chemical analyses have been made by E. G. Hallsworth and his co-workers on the soils of New South Wales. These have been published as 'Studies in Pedogenesis in New South Wales' and appear in several parts in the *Journal of Soil Science*. These investigations give much detail of certain types of soil, *e.g.* Alpine soils, red-brown earths, lateritic soils, etc., and in most instances data are given for cation exchange capacity and for clay minerals identified with X-rays.

Studies in weathering in the warm humid North Auckland Peninsula of New Zealand have been reported by N. H. Taylor

¹ *Trans. 4th Inter. Cong. Soil Sci.*, 2, 1950, p. 78; *An. Edafol. Fisiol. Veget.*, 11, 1952, p. 455.

² *Chemie der Erde*, 13, 1940-41, pp. 99, 235, 387.

³ *Chemie der Erde*, 11, 1937, p. 17.

⁴ *Op. cit.*, 1936.

⁵ *Op. cit.*, 1954.

⁶ *Zeit. Pfl. Ernähr. Dung.*, 63, 1953, p. 193.

and J. K. Dixon¹. All the rocks weather strongly, but there is a noticeable difference between the weathered products of acidic and basic rocks. The following analyses are given:

TABLE 17

RHYOLITE					BASALT			
	Rock	Wth. Crust.	Soil C ₁	Clay Mineral	Rock	Wth. Crust.	Soil C ₁	Clay Mineral
SiO ₂ %	68.8	60.0	58.1	Kaolinite	49.2	33.1	27.0	Gibbsite
*R ₂ O ₃	19.7	29.8	26.1		28.7	48.2	70.8	

* R₂O₃ includes titania.

The C₁ horizon of the soil commonly contains more than 60% clay, whereas elsewhere in New Zealand 35% clay is considered a high figure.

A number of studies of Japanese soils has been published; in particular these deal with volcanic ash and its soil-forming properties.

(3) *Investigations of Certain Aspects of Soils.* Under this heading is given a number, by no means exhaustive, of different aspects of soil formation, which are of mineralogical interest, particularly those in which new minerals are formed within the soil profile, and of those where movement of elements makes changes in the soil, *e.g.* mottling due to iron movement.

One of the most interesting studies in soil mineralogy is the influence of plants as effecting changes in mineralogical composition. It has been known for a long time that some plants accumulate certain chemical elements; for example, E. M. Chenery² has described the aluminium cycle for plants and soils; later C. Bloomfield³ described the influence of Kauri (*Agathis australis*) and other plants as iron and aluminium mobilizers. In describing the Australian alpine humus soil, A. B. Costin, E. G. Hallsworth and M. Woof⁴ identified gibbsite (by X-ray diffraction and differential thermal analysis) in a number of samples. The presence of gibbsite is attributed to the accumulation and decomposition of snow-grass (*Poa caespitosa*) litter on the surface of the soil, the snow-grass acting as an Al-accumulator. Table 5 of this paper gives the following chemical composition:

¹ 4th. Inter. Cong. Soil. Sci., 1, 1950, p. 293.

² Journ. Soil Sci., 2, 1951, p. 97.

³ Journ. Soil Sci., 4, 1953, pp. 5, 17.

⁴ Journ. Soil Sci., 3, 1952, p. 190.

TABLE 18

COMPOSITION OF SNOW-GRASS LITTER COMPARED
WITH THE UNDERLYING SOIL PARENT ROCK

Sample	No.	Depth (in.)	Loss on Igni- tion	Si O ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	SiO ₂ — R ₂ O ₃	Clay
Litter	C 9·6	0-4	33·1	68·75	16·50	2·73	1·03	6·18	—
Litter	C12·1	0-5	39·6	66·82	13·92	2·63	1·12	5·34	28·6
Subsoil	C12·3	11-19	13·9	65·56	18·66	2·90	0·74	5·37	20·5
Subsoil	C12·4	19-29	8·1	63·48	20·55	3·55	0·66	4·65	13·3
Rock*	C12·5	—	0·7	68·50	13·16	1·21	0·11	8·39	—

* Gneissic granite.

When the snow-grass decomposes the aluminium remains in the soil and forms gibbsite. The presence of gibbsite in cold climate soils may therefore not be an indicator of a previous warm climate (lateritizing conditions), but may be the results of a biological process.

G. V Jacks¹ has reviewed the Russian work on organic weathering by lowly plants, such as lichens, and it would appear that such processes should not be overlooked in soil mineralogy.

G. Brown² has studied the incidence of brown mottling in some British soils, notably gleyed soils, and has identified the iron minerals, lepidocrocite and goethite. The rate of oxidation of ferrous compounds controls whether lepidocrocite or goethite is formed.

Another common element about which there is some additional information is silica. What has been termed *organic silica* (amorphous silica) was noted in north German soils by W. von Engelhardt³ and by C. W. Correns and F. K. Schlünz⁴. Recently F. F. F. E. van Rummelen⁵ described organic silica from soils in Indonesia and suggested that removal of soil-water by action of plant roots caused accumulation of this amorphous silica. In tropical weathering, silica is removed from rocks while the pH of the leaching water remains high⁶; if drainage is impeded, this silica

¹ *Soil and Fertilizers*, **16**, 1953, p. 165.² *Journ. Soil Sci.*, **4**, 1953, p. 220; **5**, 1954, p. 145.³ *Chemie der Erde*, **13**, 1940-41, p. 8.⁴ *Zeit. Pflanz. Dung. u. Bodenk.*, **44**, 1936, p. 316.⁵ *Landb. Buitenzorg*, **25**, 1953, p. 225.⁶ C. H. Edelman, *Trans. 4th Inter Cong. Soil Sci.*, **1**, 1950, p. 308.

cannot be removed from the soil (or weathering rock) and re-silication of primarily formed gibbsite to kaolinite occurs. This was noted by J. B. Harrison¹. This fact may help to explain the presence of siliceous layers in the same horizons of Australian fossil laterites where silica was apparently mobilized but not removed; where there is little clay mineral formation taking place, because of the nature of parent rock, the silica forms layers or sheets surrounding quartz already present, and what is known as grey 'billy' results. From a knowledge of the lateritizing process and the nature of the parent rocks this explanation was put forward by D. Carroll², but unfortunately no descriptions of thin-sections of this material have been published. The Australian occurrences are quite extensive³.

Another element which is of interest, particularly perhaps in tropical soils, is titanium, and much information is available from Hawaii, as was stated earlier. Under conditions of high rainfall the inorganic colloids are characterized by very low SiO_2 content and high Fe_2O_3 or TiO_2 content. It is suggested that the titaniferous mineral has considerable cation exchange capacity.

The movement of iron has already been mentioned, but it should be noted that considerable accumulations of iron occur in many soils, particularly lateritic soils. Mobilization and recrystallization will depend on the pH of the soil solution.

MECHANICAL COMPOSITION OF SOIL AND ITS USE IN SOIL MINERALOGICAL STUDIES

The mechanical composition of soils is of interest from two main points of view; the grain-size distribution gives precision to soil descriptions and information concerning the agricultural value; secondly, the percentage amounts of some of the grades present in soils can be used to distinguish source of origin. A third use is in facilitating mineralogical examination. As the first point is established practice, discussion here will deal mainly with the second aspect.

Interest in grain-size distribution of soil materials was stimulated, especially in the United States, by the work of J. A. Udden⁴ who showed that varied kinds of materials have different grain-size distribution. The principal physical properties of soils obtained by mechanical analysis give textural significance to the several descriptive terms such as silt loam, fine sand, silt, clay, etc.

¹ *Op. cit.*, 1934.

² *Austral. Journ. Sci.*, **14**, 1951, p. 41.

³ F. Whitehouse, *Univ. Queensland Papers Dept. Geol.* 2(N.S.), **1**, 1940, p. 2; E. C. J. Mohr and F. A. van Baren, *op. cit.*, 1954.

⁴ *Augustana Library Publications*, **1**, 1898

(It should be noted, however, that there are various definitions of the grain diameter limits for these terms.) Such data have been standardized in usage by soil scientists¹.

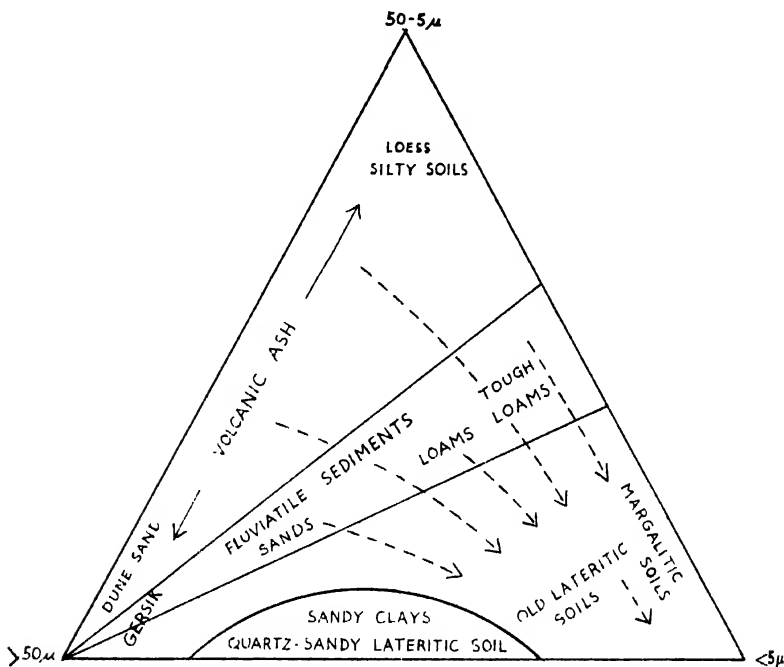


FIG. 81. Grain-size distribution in soils of various origins in Indonesia, based on data of over 100,000 mechanical analyses (from E. C. J. Mohr and F. A. van Baren, 1954).

It was long ago recognized that study of mechanical composition can be of assistance in recognition of mixed material in a soil profile; for example, J. D. White² could thus distinguish a layer of volcanic ash deposited on an older well-developed soil profile. If a number of mechanical analyses are plotted in a triangular diagram with sand (2-0.02 mm.), silt (0.02-0.002 mm.) and clay (< 0.002 mm.) as the poles, it may be found that soils fall into groups according to origin. Fig. 81 gives results of over 100,000 analyses of Indonesian soils plotted by E. C. J. Mohr and F. A.

¹ G. W. Robinson, *op. cit.*, 1950; *U.S. Soil Survey Manual*, 18, 1951; T. J. Marshall, *C.S.I.R. Bull.*, 224, 1947.

² *Meded. Landbouw. Wageningen*, 16, 1919, p. 57.

van Baren¹. The grouping of loess-loam soils of the Netherlands is similarly plotted by C. H. Edelman².

There is available in the published mechanical analyses of soils much information which could be used in interpretation of rock disintegration and weathering. When a rock weathers, either mechanically or chemically, a certain initial grain-size distribution results; for igneous rocks this distribution has been examined by W. C. Krumbein and F. W. Tisdell³, and the data have been treated statistically, whereby a sorting factor has been obtained, and the skewness of cumulative percentage curves evaluated for diagnostic purposes. In the disintegration of sedimentary rocks, such as sandstones, the residual material will have a grain-size distribution approximating that of the parent rock. W. C. Krumbein and F. W. Tisdell⁴ showed that the amount of skewing of the cumulative percentage curve about the median may be a means of identifying the kind of grain-size distribution to be expected from igneous and sedimentary rocks on disintegration into soil. From the description of a number of sandy soils⁵ it was found that, if the clay fraction (< 0.002 mm.) was removed, and the remaining grades recalculated to 100%, and plotted as cumulative percentage curves, then this would indicate the original grain-size distribution of the parental sandstone. The size distribution of sand derived from sediments had a negative skewness, whereas that of sand derived from granite had a positive skewness.

Differentiation of various parts of a soil profile can be made from the study of soil grain-size distribution curves; for example, L. de Leenheer⁶, in an examination of the soils of Yangambi, Belgian Congo, was able to show that there was great uniformity in grain-size distribution of 111 samples, for which the arithmetic mean is 0.33 mm., and the median is 0.29 mm. with a quartile deviation of 1.44, which is that of a well-sorted material. This was for samples from which the clay had been removed, because kaolinite had developed *in situ* from weatherable orthoclase and mica. The actual mean composition of the samples agrees very well with the theoretical values required by the ideal Gauss distribution for aeolian materials⁷. The results when plotted on probability paper show that this agreement is striking. A similar use of

¹ *Op. cit.*, 1954.

² *Soils of the Netherlands* (North Holland Publishing, Amsterdam), 1950, p. 168.

³ *Amer. Journ. Sci.*, **238**, 1940, p. 296.

⁴ *Op. cit.*, 1940.

⁵ D. Carroll, *Amer. Journ. Sci.*, **250**, 1952, p. 790.

⁶ *Inst. Nat. Ét. Agron. Congo Belge Pub. Sér. Sci.*, **55**, 1952.

⁷ D. J. Doeglas and W. C. Brezesinska-Smithysen, *Geol. Mijnb.*, **11** and **12**, 1941.

mechanical composition was made by H. Vine¹ in elucidating the origin of sandy soils in Nigeria.

Interesting information concerning the mechanical (and mineralogical) composition of two high altitude soils in Norway is given by H. Høltedahl². On a plateau area the soils are derived from hornblende schists; in one profile, which is a physical weathering product, the maximum grade is the 0.25–0.125 mm., with a median of 0.17 mm. The coefficient of sorting is 1.68 for one sample and 1.76 for another from the immediate vicinity. At another site, under a veneer of stones, is a well-sorted sand which grades downwards into less well-sorted material. The medians, from the top to the bottom of the profile are 0.19, 0.17 and 0.7 mm. respectively, and the sorting coefficients are 1.73, 2.51 and 4.76 for the same samples. The freshness of the mineral grains and the presence of large quantities of weatherable minerals such as hornblende, indicate that chemical weathering is at a minimum. Comparable data on the disintegration of various rocks in Alaska are given by S. Taber³.

The disintegration of granite in Germany has been studied by H. Piller⁴. The maximum grade of material in a granitic disintegration product at Fleigenberg is between 1 and 2 mm. and appears to be poorly sorted. Much information has also been obtained about the weathering products of the Brocken granite near St. Andreasberg. In this study three samples of weathering product were collected from three sites where the underlying weathering granite could be observed. Diagrams are given of the grain-size distribution and of the mineralogy of each grade of material. Other information on the disintegration products of rocks has been assembled by F. J. Pettijohn⁵.

It has long been recognized that some materials have a definite grain-size distribution and this can be used to distinguish such materials from others. Loess is such a material; in it at least 50% of the particles are between 0.05 and 0.01 mm. in diameter⁶. An investigation of the loess of southern Limburg, Holland, by J. C. A. van Doormaal⁷ shows that the important grain-size for eighty-six samples is 0.05 to 0.01 mm. The grain-size distribution for these samples is:

¹ *Commonwealth Bur. Soil Sci., Tech. Bull.*, **46**, 1949, p. 22.

² *Op. cit.*, 1953.

³ *Bull. Geol. Soc. Amer.*, **54**, 1943, p. 10.

⁴ *Heidel. Beit.*, **4**, 1954, p. 151.

⁵ *Sedimentary Rocks* (Harper, New York), 1949, p. 375.

⁶ R. J. Russell, *Geol. Soc. Amer. Bull.*, **55**, 1944, p. 1.

⁷ *Onderzoekingen betreffende de lössgronden van zuid-Limburg* (Gottmar, Haarlem), 1945.

0.05 mm.	0.05-0.01 mm.	0.01 mm.
%	%	%
2.9	72.2	24.9

The use of mechanical analysis in assisting the mineralogical description of soils has already been discussed in the introduction to this chapter, and therefore will not be mentioned further, except to state that as more refinement in methods is achieved, more use is made of size distribution of various minerals within the soil to add additional information about weathering processes. The original size of various minerals produced by different weathering environments may be of diagnostic importance; for example, cleavage and fracture of grains of such minerals as feldspar and amphibole under frost conditions, may be somewhat different than under moist warm conditions where chemical decomposition accompanies mechanical disintegration.

RELATED SUPERFICIAL DEPOSITS

Superficial deposits related to soils now to be described, are unconsolidated materials, *e.g.* loess, loose surface sands, *i.e.* the coversands of the Netherlands, drift, and volcanic ash deposits. Dune sands and desert sands are related, but are not discussed, as there is an extensive literature available.

The examination of these unconsolidated deposits consists, as in soils, of mechanical and mineralogical analyses. Identification of minerals serves to describe the deposits and to indicate mixtures of minerals of different sources, *e.g.* loess and volcanic ash.

Loess. There is an extensive literature on loess both in Europe, North America and elsewhere. In Australia loess derived from disintegration of limestones has been described by R. L. Crocker¹, who considers that excess of calcium carbonate in the Mallee group of soils is due to accretion under arid climatic conditions. In the Netherlands the loess of south Limburg was extensively examined by J. C. A. van Doormaal²; his bibliography covers the European occurrences. J. C. A. van Doormaal made mechanical and/or mineralogical analyses of some 120 samples in which there is considerable uniformity. Earlier investigators have distinguished the loess in this area from the soil developed from Cretaceous limestone³. The heavy minerals present in south Limburg loess are: opaques, tourmaline, zircon, garnet, rutile, anatase, brookite, titanite, staurolite, kyanite, andalusite, sillimanite, chloritoid, epidote, saussurite, amphibole, glaucophane and augite. The

¹ *Counc. Sci. Ind. Res. Aust. Bull.*, 193, 1946.

² *Op. cit.*, 1945.

³ J. van Baren, *op. cit.*, 1930, p. 1.

similar percentages (by grain-count) of epidote, garnet, the low percentage of staurolite, and similar amounts of kyanite and tourmaline, thus confirm C. H. Edelman's conclusion of a northern origin from his A and X mineralogical provinces¹. The minerals of the light fractions were not described, but it is presumed that quartz is a major constituent. The occurrence of loess in the Netherlands, which is part of the extensive sheet in areas of Ger-

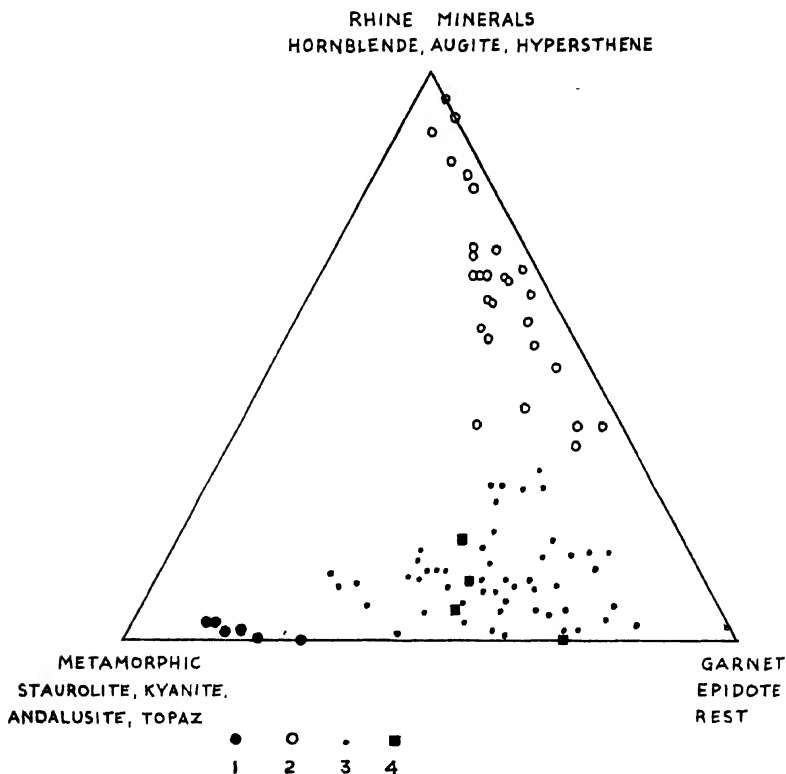


FIG. 82. Mineralogy of certain sands of the Netherlands Pleistocene showing the use of heavy mineral suites in distinguishing the various types.

1. Koalinitic sands, Sylt.
2. Rhine sands.
3. White sands, middle and east Netherlands.
4. White sands, Leth (Hamburg) and Oldenburg (after R. D. Crommelin, 1954).

¹ C. H. Edelman, *op. cit.*, 1933.

many, Belgium and northern France, has been summarized by C. H. Edelman¹. Loess and aeolian deposits of France have been described by A. Cailleux². The grain-size distribution of this loess was described in the previous section on mechanical composition (p. 496).

Recently loess has been recognized in England by W. S. Pitcher, D. J. Shearman and D. C. Pugh³ at a locality in Kent which had been geologically mapped as brickearth. The mechanical composition is similar to that of loess deposits in both Europe and the United States.

In the northern central United States and along the Mississippi River extensive areas of loess occur. Deposits of massive silts of late Pleistocene age have been described from localities distributed from eastern Colorado to Indiana, and from Iowa to Mississippi⁴. The superficial material throughout one-third of Kansas is the Peoria silt (loess) member of the Pleistocene Sanborn formation. A. Swineford and J. C. Frye⁵ have made a detailed study of the mechanical, chemical and mineralogical composition of this loess. The size distribution shows a median particle diameter between 0.051 to 0.021 mm. (4.29ϕ to 5.59ϕ). The sorting as shown by the phi quartile deviation ranges from 0.36ϕ to 0.89ϕ . The coarsest samples were those from localities adjacent to the Arkansas, Platte, Republican and Missouri River valleys, the areas from which the loess is distributed. The size-frequency distributions are similar to those obtained for loess elsewhere in the United States⁶ and for wind-blown silt⁷. The major mineralogical constituents are quartz, feldspars, volcanic ash shards, carbonates and micas. Minor accessories are black and brown opaques, leucoxene, hornblende, chlorite, biotite, epidote, garnet, pyroxenes, tremolite-actinolite, zircon, tourmaline, rutile, staurolite, titanite, sillimanite, and zoisite. The clay fraction consists of montmorillonite and illite. The presence of volcanic ash shards links the loess to the deposits of volcanic ash in western United States.

Loess in the north-eastern United States has been recognized in the Susquehanna River valley by L. O. Peltier¹; the deposits are

¹ *Op. cit.*, 1950.

² *Bull. Service Carte Géol. France*, **51**, 1953, p. 437.

³ *Geol. Mag.*, **91**, 1954, p. 308.

⁴ J. C. Frye and A. B. Leonard, *Journ. Geol.*, **59**, 1951, p. 287.

⁵ *Journ. Geol.*, **59**, 1951, p. 306.

⁶ G. D. Smith, *Univ. Illinois Agric. Exp. Station Bull.*, **490**, 1942, p. 139;
G. F. Kay and J. B. Graham, *Iowa Geol. Surv., Ann. Rep.*, **38**, 1943, p. 1;
R. J. Russell, *op. cit.*, 1944;

⁷ A. Swineford and J. C. Frye, *op. cit.*, 1951.

small, but appear typical. Loess has been described in New Jersey by J. C. F. Tedrow and P. MacClintock²; and in Massachusetts by C. L. W. Swanson, A. E. Shearin and G. A. Bourbeau³. Buried soil profiles may be associated with loess deposits; the criteria for recognition of such soils beneath loess have been discussed by J. C. Frye and O. S. Fent⁴, J. Thorp, W. M. Johnson and E. C. Reed⁵, and R. W. Simonson⁶.

Related to loess in the Netherlands are sandy deposits known as cover-sands (Dekzanden), which are considered by C. H. Edelman⁷ to be niveo-aeolian deposits of the final phase of glaciation, the Wurm. Similar deposits forming at the present time have been described from Iceland by M. G. Rutten⁸. The sand of the cover-sands appears to have come from the North Sea basin which was temporarily dry during the glacial period. The grain-size distribution has a maximum grade between 0.10 and 0.15 mm. Much interesting information on these cover-sands is obtainable from *Geologie en Mijnbouw*⁹.

Mineralogical examinations have also been applied to the elucidation of origin of other sandy deposits in northern Europe, such as the pre-glacial deposits of the Netherlands described by R. D. Crommelin¹⁰. It was found possible to distinguish brown Rhine sands, white sands, and the kaolin sands of northern Germany by their mineralogical associations using C. H. Edelman's mineral provinces. Fig. 82 indicates this mineralogical distinction. J. W. C. M. van der Sijp¹¹ made a mechanical and mineralogical distinction between two series of loams. Where there was a high clay content, the grain-size distribution is similar to that of a typical varve. The heavy minerals were identified and diagrams were made after the manner of C. W. Correns and his students, and of J. I. S. Zonneveld¹².

The re-examination by H. Schumann¹³ of data obtained for 76 samples of heath sands from south-western Mecklenburg (Germany) by P. Sabban in 1897, has provided an interesting relationship between percentage of heavy minerals and the relationship between two size fractions (0.5–0.15 mm.) and (< 0.15

¹ *Penna. Geol. Surv. Bull.*, **G23**, 1949. ² *Soil Sci.*, **75**, 1953, p. 19.

³ *Soil Sci. Soc. Amer. Proc.*, **16**, 1952, p. 203.

⁴ *State Geol. Surv. Kansas Bull.*, **70**, Pt. 3, 1947, p. 29.

⁵ *Journ. Soil Sci.*, **2**, 1951, p. 1.

⁶ *Amer. Journ. Sci.*, **252**, 1954, p. 705.

⁷ *Op. cit.*, 1950, p. 15.

⁸ *Geol. en Mijnb.*, **16**, 1954, p. 127.

⁹ *N.S.*, **14**, **2**, 1952.

¹⁰ *Mitt. Geol. Staatsinst. Hamburg*, **23**, 1954, p. 86.

¹¹ *Geol. en Mijnb.*, **14**, 1952, p. 37.

¹² *Op. cit.*, 1946.

¹³ *Heidel. Beit.*, **2**, 1950, p. 189.

mm.) grain diameter. The variations are used to indicate water or wind-sorted origin.

Drift of various kinds occurs extensively in the British Isles. Soils derived from local glacial drift in south-eastern Scotland were found by R. Hart¹ to have a similar mineralogy to that of the underlying rock. Contamination of soils by glacial drift has been described by F. Smithson² for North Wales. Both investigations give detailed description of soil minerals.

The application of mineralogical methods in an investigation of the Lafayette formation in southern Illinois has yielded considerable information concerning the source areas of the detrital minerals and several distributive provinces were recognized³.

Volcanic ash. The mineralogy of volcanic ash deposits has been studied in countries in which active or very recently extinct volcanoes occur, such as Indonesia, New Zealand, Japan and the United States.

In Indonesia recognition of volcanic ash materials in soils is of considerable importance, because the ash contributes a supplement of easily weatherable minerals which provide elements for plant growth in these soils. J. W. Retgers⁴ appears to have made one of the earliest studies of volcanic ash when he described the chemical characteristics of the Krakatoa ash. In 1931 J. van Baren⁵ described the soil which had developed in fifty years from this ash. There is much information concerning the mechanical and mineralogical composition of volcanic ashes recently deposited in Indonesia. J. A. Baak⁶ made detailed studies of the ashes from a number of active volcanoes and results of his work have been summarized by E. C. J. Mohr and F. A. van Baren⁷. There is much variation in mineral composition of the various size-fractions of the ash of Kelut, for example, as shown in Table 19⁸. F. F. F. E. van Rummelen⁹ has given mineralogical details of the ash fall of 1953, which, however, does not differ much from that of previous eruptions from Kelut.

In the United States beds of volcanic ash have long been recognized as key horizons in formations¹⁰, and they are of frequent

¹ *Journ. Agric. Sci.*, **19**, 1929, pp. 90, 802.

² *Op. cit.*, 1953.

³ P. E. Potter, *Journ. Geol.*, **63**, 1955, pp. 1, 115.

⁴ In R. D. M. Verbeek (Krakatau, Batavia), 1885, p. 178.

⁵ *Meded. Landb. Wageningen*, **35**, 1931, p. 6.

⁶ *Landbouw Buitenzorg*, **20**, 1948, p. 269; *Meded. Alg. Proefsta. Landbouw Bogor.*, **83**, 1949.

⁷ *Op. cit.*, 1954, pp. 223-236.

⁸ *Ibid.*, p. 231.

⁹ *Landbouw Buitenzorg*, **25**, 1953, p. 237.

¹⁰ C. S. Ross, *Bull. Amer. Assoc. Petrol. Geol.*, **12**, 1928, p. 143.

occurrence in Cretaceous and other formations¹. Unconsolidated ash deposits occur in the Pliocene and Pleistocene of western Kansas and have been described in considerable detail by A. Swineford and J. C. Frye². Some of the deposits have been worked commercially for many years. Mechanical analysis showed that 50% of the ash particles are less than 0.062 mm. in diameter.

TABLE 19
MINERALOGICAL COMPOSITION OF THE SANDY FRACTIONS
OF SOME SAMPLES OF VOLCANIC ASH FROM
GUNUNG KELUT
(After J. A. Baak)

Sample No.	Fraction mm.	Mutual Percentages of Minerals							Km. from Crater - = West + = East
		Opaque	Vol. Glass	Rock Frags.	Plagioclase	Augite	Hypersthene	Green Hornblende	
7046	.5 -.2	5	7	27	46	7	8	—	-9
	.2 -.1	3	20	16	46	7	8	—	
	.1 -.05	4	35	10	49	1	—	1	
	.05-.02	1	85	4	10	—	—	—	
8501	.2 -.1	3	84	—	11	1	1	—	-92
	.1 -.05	1	52	1	35	3	7	1	
	.05-.02	2	82	—	12	1	3	—	
8271	.1 -.05	12	46	2	38	—	2	—	-360
	.05-.02	4	86	—	9	1	—	—	
7049	.5 -.2	4	—	23	47	9	17	—	+36
	.2 -.1	17	15	8	45	8	7	—	
	.1 -.05	9	25	14	42	3	7	—	
	.05-.02	4	73	7	14	—	2	—	
7050	.5 -.2	—	56	7	35	1	1	—	+66
	.2 -.1	1	39	14	41	4	1	—	
	.1 -.05	8	47	5	37	—	3	—	
	.05-.02	1	84	—	15	—	—	—	
7039	.2 -.1	10	80	—	7	1	2	—	+166
	.1 -.05	4	42	2	45	2	5	—	
	.05-.02	1	84	—	13	1	1	—	

¹ C. S. Ross, H. D. Miser and L. W. Stephenson, *U.S. Geol. Surv., Prof. Paper*, 154F, 1928.

² *Op. cit.*, 1951.

Mineralogically the ash consists almost entirely of glass shards of acidic composition (SiO_2 , 70–75%; Al_2O_3 , 10–15%). The refractive index of the glass is uniform between 1.499 and 1.502, except for two Pliocene ashes where it is somewhat higher. It was found that there was a consistent difference in appearance of the individual shards of Pliocene and Pleistocene ash, the Pliocene containing platy fragments, whereas those of the Pleistocene were more ridged. Volcanic ash has also been described from many of the central States.

Weathering under suitable conditions produces bentonite beds; erosion with little weathering will cause it to be incorporated into other unconsolidated deposits such as loess, as has already been mentioned. Volcanic ash is of common occurrence in some parts of Alaska, notably Kodiak. Here, too, it tends to be mixed with loess and fluvioglacial deposits, but the presence of hypersthene with adhering glass, and of euhedral sanidine, reveals the addition of volcanic material.

FUTURE RESEARCH IN SOIL MINERALOGY

In this chapter the role of the sand-grade minerals has been explained and stressed, but for a complete mineralogical description of a soil, a knowledge of the clay minerals is also necessary; therefore information given in Chapter III, concerning the kinds of clay minerals in different types of soil, under varying climatic conditions, should also be considered here in order to obtain a complete picture of soil mineralogy.

The examination of residual minerals of soils as a guide to parentage, or for purposes of evaluating the quantity and quality of weatherable minerals present, which will provide a continuous supply of the chemical elements necessary for plant growth, is now well-established in tropical regions, where rapidity of action of soil-forming processes quickly removes the soluble constituents of minerals. A number of examples has been given of such investigations. Mineralogy provides, too, a useful tool for unravelling the mixing of soil-materials in a profile. Perhaps the simplest of such mixed profiles can be expected to occur in alluvial soils, in which the various layers may contain mineral grains from different sources.

Much still needs to be done in the field of weathering and soil profile development, both mineralogically and chemically; and understanding of the chemical environment of rock weathering and soil formation can only be obtained by detailed study of individual soil profiles in different areas. The pioneer work of J. B. Harrison¹ pointed the way and many excellent studies of tropical

¹ *Op. Cit.*, 1934.

soils have resulted. The development of rapid X-ray techniques for identification of clay minerals has opened up a whole new field in soil profile development studies; uncertainty and conjecture in mineralogical interpretation of chemical analyses of soils can now be replaced by facts, which still, however, require interpretation in the light of soil-forming processes. The most pressing needs here are methods for the more precise quantitative determination of the clay minerals. Data should be accumulated for the environments in which soil clay minerals are formed, persist, or disappear from soil profiles. Much is already available in soil-literature, but it is scarcely evaluated mineralogically in more than a few instances. Chemical analyses of soils provide a wealth of information for their mineralogical investigation; to cite one instance, the titanium content of Hawaiian soils¹ varies with the climatic and drainage conditions, but very few microscopic examinations have been made of the actual minerals present, which are stated to be ilmenite and anatase. pH determinations are available for innumerable soils and soil profiles; so too are figures for exchangeable cations; both can profitably be used to identify soil chemical environments which have a most important bearing on stability and weathering of mineral grains in soils.

The mechanical composition of soils is important in that, firstly, it tells something of the original size of grains formed by breakdown of rocks, pre-supposing that these are solid rocks such as granite or gabbro; and, secondly, by development of horizons within the soil-profile, it reveals the soil-forming processes acting on the material as a whole (*e.g.* transfer of clay from one horizon to another). There is available a wealth of information on mechanical composition of soils from various parts of the world, but it has scarcely been examined from the statistical point of view with regard to the size-distribution of different kinds of material from different parent rocks, although use is made of the range in sizes of grains in loesses and sandy soils. That this information has a real use is shown by the work of Dutch soil scientists in Indonesia². Interpretation of mechanical analyses of soil can help to elucidate problems of mixing of soil material from different sources, *e.g.* a sandy surface layer above clay material developed by the weathering of basalt.

The colour of black soils needs further investigation, particularly with regard to the role of organic matter and the kind of clay minerals present.

Soil-mineralogy has progressed in the last decade and a half (for English-speaking people) from a rather interesting side-line of

¹ G. D. Sherman, *Proc. Amer. Soc. Soil Sci.*, **16**, 1952, p. 15.

² E. C. J. Mohr and F. A. van Baren, *op. cit.*, 1954.

sedimentary petrology, to an important independent position in which its main function is to add precise information to soil descriptions, and to assist in the interpretation of soil-forming processes. The pioneers in the use of soil mineralogy as a practical means in interpretation and economic evaluation of tropical soils are the Dutch, much of whose literature is not readily available since it is published in the Dutch language.

Soil mineralogy provides the ideal stepping-stone between geology and soil science; it is especially important to an understanding of the size distribution and mineralogy of materials available for removal and redeposition by erosion agents.

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CHAPTER VIII

APPLIED SEDIMENTARY PETROLOGY

Introduction—Asphalt in Building Construction—Building Technology—Cement and Concrete Technology—Ceramics—Fillers—Forensic Science—Glass Technology—Medicine (Industrial Maladies)—Moulding (Foundry and Furnace) Sands—Refractory Materials—Road Construction and Research—Water Supplies.

INTRODUCTION

ACADEMICALLY, as we have seen, sedimentary petrology is a firmly established branch of geological science and its functions are widely appreciated wherever sediments constitute the object of investigations. We have further learned in this book to what extent certain major industries have made use of this knowledge, more particularly where stratigraphical problems demand positive solution for important economic motives. The influence of the petroleum industry particularly on rapid evolution of this petrology has already been stressed. No less important today are many other professional and commercial callings wherein the principles of the subject and the practice of its tenets play an important, though possibly less generally realized, part in the march of progress.

It is the intention in this chapter briefly to review some of the less widely known applications of the subject, in the hope that this will serve to give the reader an idea of its almost unlimited scope in everyday life, also to stimulate a breaking of fresh ground wherever petrographic methods may seem to have legitimate and profitable entry. No attempt is made to cover every ramification; only the more important modern adaptations can find space here. A short bibliography of relevant references at the end of each section will, however, enable the reader to follow up in appropriate detail such applications as may be of interest.

ASPHALT IN BUILDING CONSTRUCTION

The increasing use of mastic asphalt in water-proofing buildings, especially those constructed of reinforced concrete, by the laying of horizontal and vertical dampcourses, roofs, skirtings, fillets, etc., also in the design of interior floorings, both black and coloured,

has continued to develop in this country as a highly important and specialized industry, which originally had its beginnings many years ago in Europe.

Mastic asphalt is essentially a mechanical mixture of a rock aggregate and specially selected asphalt cement in such proportions as will give a product which, when heated, can be worked with a float into the desired position, thereafter setting into a compact, voidless, impervious mass. The latest B.S. definition of mastic asphalt is 'A type of asphalt composed of suitably graded mineral matter and asphaltic cement in such proportions as to form a coherent, voidless, impermeable mass, solid or semi-solid under normal temperature conditions, but sufficiently fluid when brought to a working temperature to be spread by means of a hand float'¹.

In the latter part of the nineteenth century, much of the building mastic asphalt used in this country was made exclusively from imported natural rock asphalt, *i.e.* naturally impregnated bituminous limestone, mined or quarried in the Bassin de Seyssel, Departments of Ain and Haute Savoie, France, and elsewhere. The word 'Seyssel' thus came to be the hallmark of a well-recognized product and a household word among the older architects, surveyors and engineers. It was customary, then, as it still is in a few cases today, to specify simply 'Seyssel' asphalt, meaning by that a natural rock asphalt mastic, the aggregate of which was derived solely from the Seyssel district. The fact that no commercial deposits of comparable bituminous limestone occur in Britain supported the 'die-hard' belief that 'Seyssel' asphalt was indeed the best possible material.

Actually other parts of France, *e.g.* Department of Gard, also other countries such as Italy, Sicily, Germany and Switzerland, produce high-grade bituminous limestones suitable for manufacturing good quality natural rock asphalt mastics. Such limestones in a majority of cases have no geological and certainly no geographical connections with 'Seyssel', so that technically considered the significance of that particular name is today more apparent than real.

With the rapid progress of petroleum technology, especially in connexion with refining of petroleum, there were gradually placed on the market various standard grades of asphaltic bitumen used successfully not only for fluxing the bitumen in naturally impregnated rocks and in fluxing native bitumen such as Trinidad Lake Asphalt, but also capable of direct mechanical admixture with ordinary crushed limestone powder to form mastic asphalt products. Thus were the so-called 'synthetic' mastics introduced; these had a material commercial advantage over natural rock asphalt

¹ B.S.1418: 1958, p. 5.

mastics in that the former could be manufactured in this country without importing foreign rock and could, therefore, be produced much more cheaply. The development of these 'synthetic' mastics was enormous, especially after the First World War, so much so that from the standpoint of commercial production and use, natural rock asphalt mastics to a large extent gave place to them, though technical opinion was and even now is sharply divided on the question of relative merits of the two types, especially concerning durability with age. Certainly, the natural rock products are more expensive and are still claimed by their protagonists to be far superior to mastics compounded of British limestone, asphaltic bitumen or any other type of asphalt cement¹. However, we are not here concerned with any technical controversy on this matter but rather with the illegitimate use of 'synthetic' mastic where contracts have definitely called for natural rock mastics.

For a long time (up to about 1929) there was no generally recognized method of analysing these mastics which would give unequivocal evidence as to the source of origin of the aggregate. Chemists grappled with the problem from the standpoint of the bitumen involved, but soon found themselves up against serious difficulties in recovering it in unchanged form from the product, quite apart from the impossibility of isolating inherent bitumen in the natural rock (where used) from that which had been added as a fluxing medium. The geologists' attack lagged still farther behind and consequently for some years substitution of 'synthetic' for natural rock asphalt mastic, where practised, went unchallenged. All that was subsequently changed by the building up of a palaeontological-cum-petrographic technique which is now highly specialized and, in the hands of experts, gives the desired evidence in practically all cases.

In the first place, each of the well-known natural rock asphalts from recognized sources in France, Germany, Italy and Switzerland has been exhaustively studied as regards the actual limestones involved, their micro-organisms, inorganic mineral components (including heavy mineral suites), inherent structures, manner and degree of impregnation by the bitumen and, in the crushed state, as regards characteristic shapes of the particles involved. In the author's laboratory, many hundreds of reference microscope slides depicting each of the above features have been accumulated over a period of more than thirty years and are used for comparison with aggregates segregated from mastic asphalts under test. Such a collection is a *sine qua non* to correct interpretation of evidence

¹ C. M. Watkins and C. M. Gough, The Use of Asphalt Mastic for Roofing, *Dept. Sci. Ind. Res., Building Research Spec. Rep.*, 25, 1937.

derived from direct tests. On the chemical side, the inherent bitumen of these rocks has been extracted and studied in great detail by modern methods, involving not only standard physical tests of characteristics, but also chemical determinations, such as asphaltene content, saponification and acid values, also colorimetric analyses, both of the bitumen itself and its segregated asphaltenes, coupled with relevant ultra-violet fluorescence tests of both bitumen and natural rock¹. All this evidence aids classification, comparison and differentiation of the several natural rock asphalts now commercially exploited and serves, together with petrological data, to fix identity of a particular rock in the raw state.

In the case of 'synthetic' mastic asphalt, in this country it is customary to use for the most part Carboniferous Limestone from such areas as the Mendip Hills, the Peak district of Derbyshire, North Wales, Northumberland, etc. This rock, in its crushed state is used as aggregate for the mastic concerned (except in special cases where sand, slate dust, etc., may be incorporated for certain specific reasons) and is readily recoverable in its original state for petrological examination, the mode of attack on such material, with a view to its identification, following normal petrographic technique for the study of incoherent sediments. Again, a large and representative collection of microscope preparations must be available for reference, involving thin sections of the original consolidated rocks, carefully localized as to every main centre of supply, slides of heavy mineral residues extracted from such powders, slides specially selected to show micro-organisms characteristic of particular developments and so on. Intimate stratigraphical knowledge of these Carboniferous Limestone occurrences is equally essential, as is the case with other limestones occasionally employed for the purpose and, what is even more important, where such rocks are mineralized, *e.g.* Northumberland, Cumberland, Derbyshire and elsewhere, the nature, extent and main areas of development of the resultant ore-bodies must be known.

Space prevents detailed discussion of the various collective 'indices' of different British limestone powders used in the asphalt industry today, but suffice it to say that Carboniferous Limestone of one area is by no means uniform in petrographical or palaeontological characteristics with limestone of similar age in another. For instance, different developments vary in the amount and character of crystalline calcite present; in development of dolomite; in the larger organic components the fragmentary remains of which are frequently recognizable in the crushed rock; in the

¹ L. J. Chalk, The Recovery of Bitumen, *Journ. Soc. Chem. Ind.*, **56**, 1937, p. 156.

nature of the foraminifera present; in the nature of the oolite grains where prevalent; in the nature and amount of inorganic matter such as silica and iron. The same applies to the heavy mineral constituents which, as segregated by contemporary methods, are generally much more prolific than is usually imagined for calcareous rocks.

The best known example of a limestone 'indicator' is the fluorite characteristic of the Carboniferous Limestone of the Matlock district, Derbyshire, whence are derived considerable quantities of powder used in manufacture of 'synthetic' mastic asphalt. This mineral is so prolific that even the smallest amount of aggregate recovered from a sample of mastic involving this particular powder will reveal its presence. Further, it is not simply a question of identifying fluorite *per se*, but of observing its special physical and optical characteristics which distinguish it even from other fluorite developments. Obviously, as this Derbyshire type of fluorite is unknown both in other British limestone developments and in any of the European natural rock asphalts employed, its presence *ipso facto* points to the source of origin of the aggregate and where contamination or substitution of a natural rock asphalt has occurred, the fact is immediately betrayed by observation of the blended 'indices' of both rocks involved. It is further to be noted that this *type* of fluorite is absent from the components often employed in mastic asphalt apart from the filler, namely the various 'grits' used as coarse aggregate and particularly from the inherent heavy mineral residue of Trinidad Lake Asphalt, so frequently a constituent of the asphalt cement used, but which itself carries a distinctive and easily recognized mineral suite.

Two other examples may be quoted of British limestone developments, characterized on the one hand by doubly terminated quartz crystals of remarkable definition and individuality and on the other by barite possessing distinctive traits. Thus, the evidence in every case is not far to seek in the hands of expert investigators. In fact, in some instances, it is even possible to estimate approximately the amount of contamination by British limestone which has affected an otherwise pure imported natural rock asphalt mastic.

Another diagnostic method of differentiating between naturally and artificially impregnated limestone particles is by close microscopical study of the associated brown matter, *i.e.* bitumen. In the case of naturally impregnated rocks the bitumen penetrates the finest interstices of grains and particularly the innermost walls of cells, chambers or other organic (fossil) structures. This is seldom, if ever, achieved in the case of a purely mechanical admixture of hard, crystalline limestone filler and asphaltic bitumen whatever its character. In the latter case, staining is superficial, being a

survival of the film made to coat the particle during the mixing process. With naturally impregnated limestone, the rock is in nearly all cases softer in character, much less crystalline and far more permeable, hence it lends itself initially to intimate and thorough penetration by the original mother-fluid, *viz.* crude petroleum, which gave rise to the bitumen as now observed.

Petrological studies of the mineral matter in native asphalts, *e.g.* Trinidad Lake Asphalt, Cuban Asphalt, are conclusive in the evidence their characteristic heavy mineral suites provide as a means of their identification; frequently where chemical and physical methods fail to give decisive results, such evidence is quite convincing. Much yet remains to be done in extending these methods to various native asphalts containing mineral matter and as yet relatively little known in this country.

Finally, there is the fact that recovery of the total bitumen from mastic asphalt products is now a much more exact process and that, in certain cases, comprehensive testing of the bitumen so obtained furnishes invaluable supporting evidence of the presence or absence of naturally impregnated asphaltic limestone¹. (See also under Road Construction and Research, p. 582.)

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¹ L. J. Chalk, *op. cit.*

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BUILDING TECHNOLOGY

Sedimentary petrography has many direct applications in modern building construction, concerned as it is with such varied types of natural and the ingredients of artificial stones.

Natural stone, whether utilized as primary constructional material or purely as decorative facing or for other purposes, should never be selected haphazardly, but rather with due regard for locality, source, durability with age, facilities which it offers for fashioning into set designs and, where employed externally, with particular reference to its weathering tendencies, especially in coastal, industrial and urban areas. The invaluable researches of the Building Research Station (Department of Scientific and Industrial Research) have, over a long period of years, done much to educate public opinion as to the reasons why some building stones are superior to others in service. For instance, the problem of weathering of natural building stones has been tackled on a scientific basis and in the understanding of the chief factors involved, chemical, geological and physical influences have all been studied, their effects correlated and pertinent deductions drawn therefrom.

The weathering of sandstones, limestones (including magnesian limestones) is dependent on inherent natural defects in the selected rocks, such as soft beds, vents and shakes, on unfavourable structures, on bad workmanship in selecting and fashioning the stone, on the effect of atmospheric pollution in congested cities and industrial areas, on temperature changes, moisture, frost, action of inherent soluble salts (florescence) and in some cases of organic agents of decay (bacteria, lichens, etc.). The application of the microscope to the study of many selected building rock-types

by means of thin sections, especially resin-impregnated bodies, (Vol. I, p. 94), is a technique which we owe largely to the Station and assessment of macro- and micro-porosity by this means, to mention only one phase of such research, has proved to be of vital importance in interpreting the phenomena observed.

In the United Kingdom sedimentary rocks figure conspicuously both in ancient and modern buildings. Chief among these building stones are undoubtedly the famous Portland limestones from the Isle of Portland, Dorset, which include oolitic limestone, locally known as 'Roach'; the fine-grained variety is used specially for plinths, bridges and abutments, the 'cavernous' (shelly rock) type being employed particularly for sea-walls, dock-yards and harbour construction. The 'Whitbed' is the chief oolitic type from which block-stone is prepared; it is essentially this bed which furnishes typical Portland Stone. Other well-defined beds include the 'Base Bed' oolitic limestone and a compact crystalline type, 'Perrycot', which can be cut into large rectangular slabs and fashioned for decorative work such as wall-linings, columns and pilasters. These varieties of Portland Stone are macroscopically conspicuously differentiated, but when studied by means of thin sections under the microscope, their inherent characteristics and structural differences are soon apparent.

Somewhat similar to the oolitic Portland limestones of Dorset are the famous 'Freestone' and oolitic limestones of the Great Oolite age, as developed in the quarries and underground workings near Bath, Somerset.

Apart from these Jurassic building stones, certain sedimentary rocks from other stratigraphical horizons are widely employed in the building industry for their high quality, uniform texture, pleasing appearance and durability in service. Among these may be cited the Old Red Sandstone of Lanarkshire and Dumbartonshire; the Carboniferous Limestone of the Mendips and the Peak District; the Pennant Sandstone of the Coal Measures of the Bristol district and South Wales; the magnesian limestones (Permian) of the Mansfield district, Nottinghamshire; the fine-grained micaceous sandstone known as the 'St. Bees Head Freestone' of Cumberland; the Ketton Stone (Lincolnshire Limestone) from the Inferior Oolite of Rutland, also limestone of similar age known as the 'Ancaster Freestone' from Lincolnshire. This list can be considerably extended, but those examples have been selected not only because of their importance in the building industry, but also because representative samples of each of these rocks form an excellent basis of study for comparative data for the student who is interested in the application of the petrography of sedimentary rocks to natural building constructional materials.

Next in the category of rocks employed as building and ornamental stones come slates. These, however, as ultimate products of dynamic metamorphism of fine argillaceous matter, are necessarily excluded from a treatise on sedimentary rocks.

no description of modern building materials would be complete without at least passing reference being made to this ancient and important industry. Apart from its primary function as roofing and dampcoursing material, slate finds extensive use for monumental purposes, also as surfacing for flat roofs, pavements, brewery tanks, aquarium construction, laboratory balance room equipment, etc., the noted areas of production being Blennau Ffestiniog, North Wales and Delabole, Cornwall.

In latter years considerable technical research has been conducted for the purpose of extending the use of slate, for improving its appearance (artificial colouring) and for utilizing slate-waste¹. Part of this research has involved a technique which includes methods well known to petrographers. Mineral composition, mechanical analysis of dust, determination of particle size, classification of superfine material, etc., are among some of the data sought and achieved by petrologists who have taken part in these investigations; it will readily be appreciated to what valuable use the microscope can be put in determining some of these properties of slate and its products.

In sharp petrological contrast to these slates are certain sedimentary rocks, 'Tilestone', 'Flagstone', used for roofing purposes. The famous 'Stonesfield Slate' (Great Oolite series) is a good example of the type of rock involved. This 'slate' has been employed to great picturesque advantage in many Cotteswold buildings, as those familiar with that country are well aware. The rock is essentially a thinly bedded sandy limestone, flagstone rather than true slate, since it possesses no cleavage which is the fundamental characteristic of real slates. 'Cotteswold Slate', as it is known, has been worked for centuries at various places, especially in the North Cotteswolds and is now principally exploited from Salperton, Naunton, Eyford Hill, etc. The principal 'slate' bed is known as the 'Pendle' and a microscopical study of this and associated types soon reveals the structure and composition which together determine the characteristic weathering of these rocks.

Passing from consolidated to incoherent sediments employed as building materials, it is common knowledge that practically every type of sedimentary deposit, whether of mechanical, organic or chemical origin, finds some economic use in constructional work. Gravel, sand, clay, marl, limestone, gypsum, to mention a few fundamental raw materials, enter into the manufacture of the

¹ See section on Fillers, p. 554.

chief artificial (including many forms of decorative) products incorporated in modern buildings.

The utilization of these materials gives rise to an enormous number of manipulative problems; each has its own particular technique, wherein chemists, petrologists and physicists may pool their specialized knowledge to ensure that only proper raw materials are selected for the particular purpose in view and, further, to control scientifically such process of manufacture as may be necessary to the ultimate product. It is, in fact, the sum total of this knowledge concerned with so many variable raw materials and the still greater number of artificial products made therefrom which constitutes the wider subject of building technology as we know it today, constituting an important branch of applied science of modern growth, one which is making progressively rapid strides at the present time.

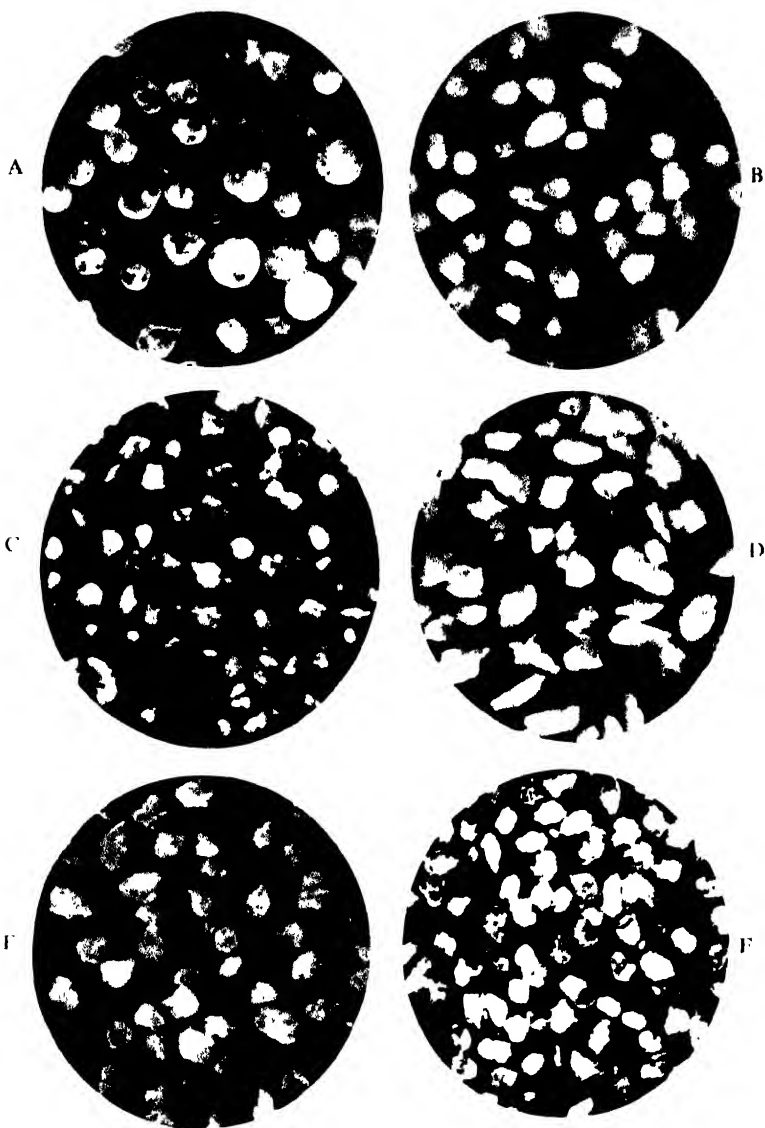
The following is a list of the principal raw materials used in the building industry and the products derived from one or more of them:

RAW MATERIALS	PRODUCTS
Gravel	Concrete.
Sand	Cement and lime mortar; concrete; plaster; bricks; sand-lime bricks; tiles.
Clay	Bricks; tiles; ceramic products; fire-bricks; refractories.
Marl	Cement.
Limestone	Lime; hydraulic lime; hydrated lime; Portland cement; lime putty; plaster.
Gypsum	Plaster.

In the investigation of these raw materials, the technique follows closely the various methods laid down in this book for determining physical constants. In the case of gravel aggregates for concrete, it is desirable that the rock (flint, chert, limestone, etc.), whether in natural state or crushed, shall be hard, strong and durable, clean and as free as possible from authigenic and organic matter. Deleterious materials such as coal, ash, breeze, pyrite, slag and porous components must be excluded. Much the same applies to the fine aggregate (sand), where it is desirable that all silt, clay and organic matter should be absent. Both coarse and fine aggregates must comply with conventional gradings, depending on the design of the particular concrete mix laid down.

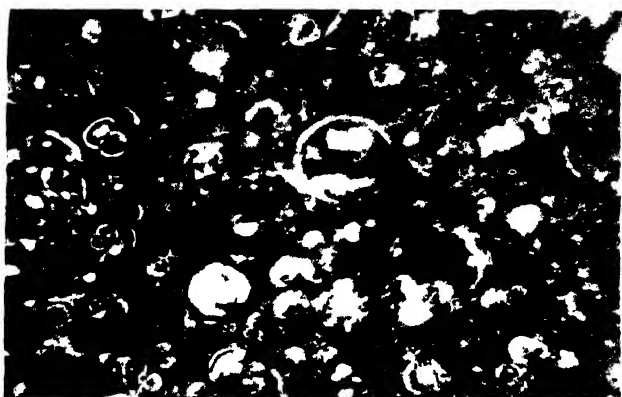
Sand for plaster, bricks, tiles, etc., is chosen largely with regard to local resources, composition and grading, and the tests which are necessary to determine suitability are, in part, described in appropriate B.S. specifications¹.

¹ B.S. 882: 1954; B.S. 1198: 1955; B.S. 1257: 1945.



A-F. AGGREGATES FROM VARIOUS ASPHALTIC LIMONITES

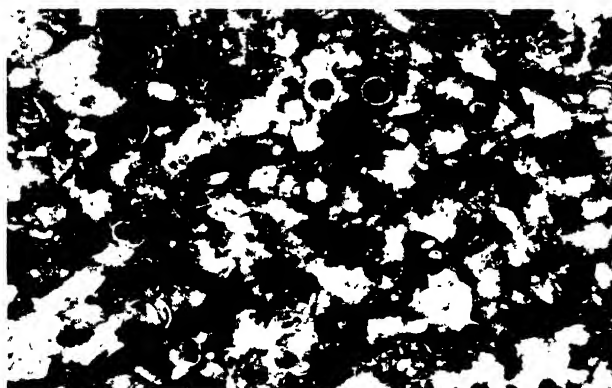
- A Boeton, Dutch East Indies [x 16]
- B Seafa, Italy, [x 16]
- C Sicily, [x 30]
- D St. Jean de Maruéjols, Gard, France. [x 19]
- E Pymont, Seyssel, France [x 16]
- F Val de Travers, Neuchatel, Switzerland [x 19]



B



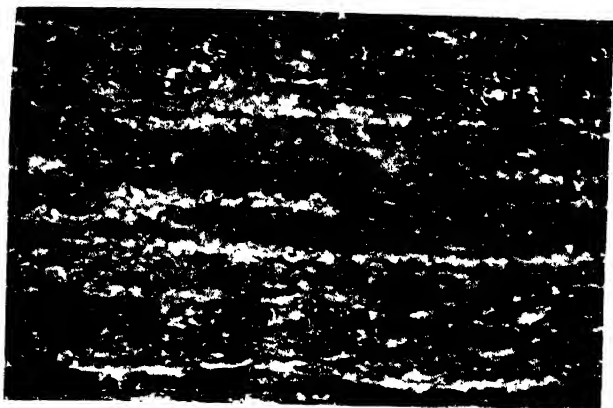
C



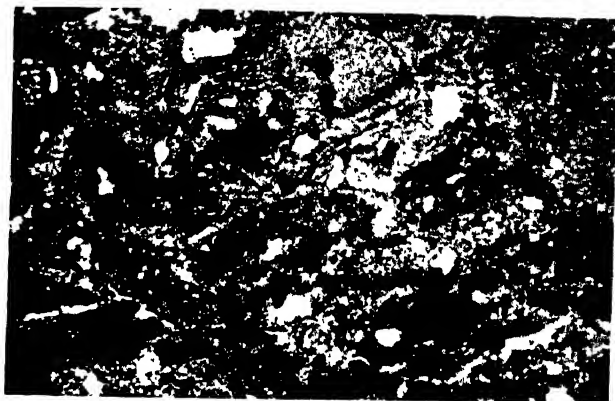
A, B, C. ASPHALTIC LIMESTONES (Natural Rock Asphalts)

- A Boeton, Dutch East Indies (*Foraminifera*) [x 29.]
 B Scafa, Italy [x 24.]
 C Sicily [x 35.]

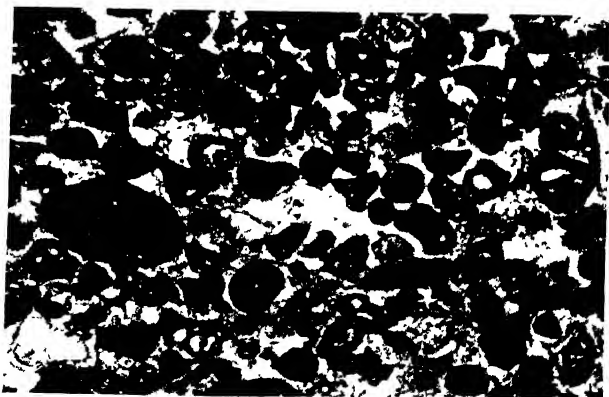
A



B



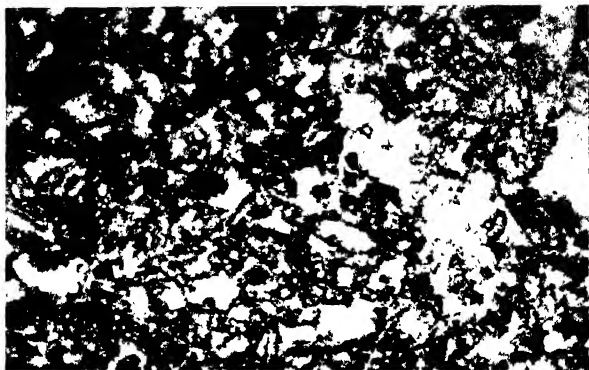
C



A, B, C. ASPHALTIC LIMESTONES (Natural Rock Asphalts).

- A. St Jean de Maruéjols, Gard, France [x 17]
- B. Montrotier, Seyssel, France [x 17]
- C. Pyramont, Seyssel, France [x 21]

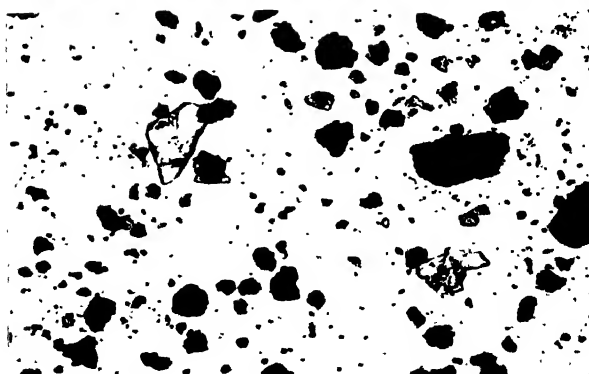
A



B



C



A, B. ASPHALTIC LIMESTONES (Natural Rock Asphalts).
C. CONTAMINATED ROCK ASPHALT POWDER.

- A. Val de Travers, Neuchatel, Switzerland [x 33]
B. Vorwohle, Hanover, Germany [x 30]
C. Natural Rock Asphalt Powder contaminated with
British Carboniferous Limestone (Note
Fluorite grains) [x 51]

With clays used for brick and tile making, investigations include colour, hardness, behaviour on drying, manner in which the dry clay breaks, mechanical analysis, specific gravity, degree of plasticity achieved with known water-content, tests on weathered material, pugging tests, cutting tests, etc.; the chemical composition must be known and firing trials on the raw clay carried out to give information as to how it will stand up to the normal process of burning.

Selection of suitable calcareous rocks for the manufacture of cement is largely a matter of local resources and utilizing either an extremely pure form of the carbonates, such as chalk, together with such clay as may be best suited for blending; alternatively, by employing less pure limestones or marls which in some cases can be burned direct. Similarly, selection of pure raw material for calcium sulphate plasters is a matter depending to a large extent on mineralogical purity, freedom from adventitious rock fragments and so on, and the tests necessary to determine the favourable qualities of such material are again in part within the province of the sedimentary petrologist.

One obstacle to narrowing the gap between technical progress and empirical trade custom, for instance in the employment of mechanically formed aggregates such as ballast, gravel, sand, etc., has in the past been the lack of a generally agreed nomenclature for the diverse materials known and used in the building industry. Tradition in this industry, as in many others, dies hard and it has taken the combined influence of government departments, standardization committees and mandatory codes of practice to remove prejudice to scientific procedure; in other words, to make the tools of building science precise factors in its everyday commercial applications. In the author's experience it is highly desirable that standardized nomenclature should, in fact, be employed at all levels so that both builder and scientist are talking the same language. In an effort to clarify the position concerning aggregates, the author some years ago published a number of definitions which have since constituted a basis of discussion in appropriate places¹. No apology is needed for inclusion of some of these definitions here, with others of later derivation, many at least familiar to the sedimentary petrologist. The schedule has been extended to include several other building materials. In each case the authority for the definition as quoted is given in parenthesis.

AGGREGATE. (1) Inert incoherent material composed of gravel, sand, crushed natural rock, or suitable crushed synthetic products, comprising slag, clinker, or combinations thereof, with which specific

¹ The Nomenclature of Aggregates. Ballast, Sand and Allied Trades Assoc. *Bull.* 2, July 1936, p. 5.

bonding media are incorporated to form mortar, concrete, asphalt, tar macadam, etc. (H.B.M.).

(2) Broken stone, slag, gravel, sand or the like which, when held together by binding agent, forms a substantial part of such materials as concrete, asphalt, coated macadam or the like. Aggregates are described as 'coarse' or 'fine' according to whether they are retained on or passed by a sieve of specified aperture size ($\frac{3}{8}$ in. for concrete aggregates and $\frac{1}{8}$ in. for aggregates used in bituminous materials). (B.S.892 : 1954.)

ALL-IN AGGREGATE. A term used for both all-in ballast and crusher-run material. (B.S.892 : 1954.)

ALL-IN BALLAST. Aggregate containing a substantial proportion of all sizes (including sand) below a stated maximum, as obtained from a pit, river-bed or sea shore. (B.S.892 : 1954.)

ARTIFICIAL STONE (CAST STONE). A form of precast concrete in which the finished surface resembles that of natural stone. (B.S.1217: 1945 and B.S.892 : 1954.)

ASPHALT. See p. 519.

BALLAST. (1) Small stones mixed with grit, sand and clayey materials in such proportions as to produce, when consolidated, a coherent layer, in which the major portion of the particles is retained on standard sieve having 4 square meshes to the lineal inch (England and U.S.A.). (*Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.*)

(2) Ballast means (a) gravel, shingle, ashes, or clinker, or (b) any material commonly known in the Building and Engineering Trades as ballast, stone chippings, granite chippings or hard-core of brick, stone, stone ware or concrete, or (c) any similar material commonly known and used in the said trades as an aggregate for constructional work. (*Weights and Measures Act, 1936.*)

(3) The term 'ballast' is taken as meaning all mixtures of stone and sand, of which the voids in the stones are filled with sand. (Original definition, *Ballast, Sand and Allied Trades Association.*)

BEDROCK. (1) Any hard rock-bed underlying soft deposits classed as soil in the engineering sense. (B.S.892 : 1954.)

(2) Geologically, consolidated rock lying immediately below drift deposits, *i.e.* soil, gravel, boulder clay, alluvium, etc. (H.B.M.)

BING. A large heap of waste mineral material which may or may not be a suitable source of road material. *Note.*—This term is usually applied to the heaps of burnt or unburnt shale at a colliery. (B.S.892: 1954.)

BOULDER. (1) Naturally eroded and isolated derivative of a consolidated rock. In Britain usually applied to detached rounded rock fragments larger than egg-size pebbles. In U.S.A. is restricted to detached rock masses having a minimum major dimension of 256 mm. (10 in.). (Based on C. K. Wentworth's classification.) (H.B.M.)

(2) A rounded or subangular stone or piece of rock of relatively large size. (B.S.892 : 1954.)

BRICK (CLAY BUILDING). 'A building unit made of hard inorganic

material, of a size that can be conveniently handled with one hand, rectangular in form, and of such proportions that the length equals twice the width plus one mortar joint, whilst the depth is less than the width.' (B. Butterworth, *Bricks and Modern Research*, Crosby Lockwood, London, 1948.)

BRICK (CLAY ENGINEERING). A building or constructional brick characterized by high compressive strength, low moisture absorption and high durability. (Based on B.S.1301 : 1946.)

BURNT SHALE. Shale which has been altered by combustion, usually spontaneous, in a colliery tip or bing. (B.S.892 : 1954.)

CEMENT¹. A material which, if added in a suitable form to a non-coherent assemblage of particles, will subsequently harden by physical or chemical means and bind the particles into a coherent mass. (B.S.892 : 1954.)

CHIPPINGS. (1) Rock fragments produced by mechanical crushing process, essentially of angular shape and ranging in size from 1 to $\frac{1}{8}$ in. (H.B.M.) (See also B.S.63 : 1951.)

(2) Crushed angular stone fragments of single-size material of nominal size between $\frac{1}{8}$ in. and 1 in. (B.S.892 : 1954.)

CLAY. (1) A natural deposit of extremely fine texture usually plastic when wet and hard when dry and consisting substantially of disintegrated rock particles less than 0.01 mm. (0.0004 in.) in diameter. (Based on P. G. H. Boswell's classification.)

(2) (a) Colloidally fine complex silicates formed by the natural decomposition of igneous rocks.

(b) In the particle size analysis of soils: mineral particles smaller in size than 0.002 mm. (B.S.892 : 1954.)

COBBLE. (1) A naturally eroded derivative of consolidated rock, of similar character to 'boulder' (*q.v.*), having a minimum major dimension of 64 mm. (2½ in.) and maximum dimension of 256 mm. (10 in.). (Based on C. K. Wentworth's classification.)

(2) A rounded or subangular stone, of size between 3 in. and 8 in. approximately. (B.S.892 : 1954.)

CLINKER. The semi-vitrified and mainly inorganic residue of combustion of domestic refuse, solid boiler fuel, etc. (B.S.892 : 1954.)

CONCRETE². A mixture of mineral aggregate with a cementing agent which, on chemical or temperature change, binds the whole into a solid mass. When no cementing agent is specified, the use of a cement of Portland cement type is generally understood. (B.S.892 : 1954.)

CRUSHER-RUN STONE. Rock that has been broken in a mechanical crusher and has not been subjected to any subsequent screening process. (B.S.892 : 1954.)

FILLER³. (1) Finely ground mineral matter or other inert substance

^{1, 2} See also section on Cement and Concrete Technology, p. 536.

³ See section on Fillers, p. 554.

commonly employed as a constituent of the matrix in certain constructional materials, *e.g.* asphalt. (H.B.M.)

Note.—Fillers for certain road-surfacing materials (excluding Portland Cement or Blast-Furnace Cement) must all pass an 85 B.S. sieve, and not more than 15% must be retained on a 200-mesh B.S. sieve. (See B.S.594 : 1958.)

(2) An inert, finely divided powder employed to give body to a bituminous binder or to fill the voids of a sand. The portion impalpably fine is called 'flour'. (*Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.*)

(3) Relatively fine material mixed with the aggregate for the purpose of reducing the voids. (Not applicable U.S.A.) (*Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.*)

(4) A finely divided mineral powder added to road tar, bitumen or the like, or to a mixture containing the same, in order to effect some desired change in the properties of the binding material. (B.S.892 : 1954.)

FILLING. Material used for raising earthworks to formation level. (B.S.892 : 1954.)

FLAGSTONE. A flat slab of natural or artificial stone or pre-cast concrete used for paving footways. (B.S.892 : 1954.)

FLOUR. The impalpably fine portion of a filler. (*Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.*)

GRANULES. A loose detrital sediment in which the grade size from 2 mm. (0.08 in.) to 4 mm. (0.16 in.) predominates. (Based on C. K. Wentworth's classification.)

GRAVEL. (1) Naturally eroded derivatives of consolidated rock or loose detritus in which the minimum grade size is 2 mm. (0.08 in.) (Based on P. G. H. Boswell's classification.)

(2) Colloquially applied in the building trade to specific concrete aggregates which include pebbles and sand.

(3) Small stone, usually waterworn, sometimes mixed with finer materials, occurring in natural deposits. (*Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.*)

(4) A non-coherent, natural, detrital, mineral aggregate, consisting mainly of rounded pebbles or subangular rock fragments, or both. (B.S.892 : 1954.)

GRIT. (1) A sandstone composed of angular particles. (H.B.M.)

(2) A term frequently employed in the trade for aggregate of graded particles (*e.g.* flint), ranging from $\frac{1}{8}$ in. to $\frac{1}{4}$ in. or less. (H.B.M.)

(3) Fine sharp gravel or coarse sand. (*Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.*)

HARDCORE. Material consisting of pieces of stone, broken brick, or the like, which when compacted forms a stable base. (B.S.892 : 1954.)

HOGGIN. (1) Small stones, mixed with grit, sand and clayey materials in such proportions as to produce, when consolidated, a coherent layer in which the major portion of the particles passes a standard sieve

having 4 square meshes to the lineal inch and is retained on a standard sieve having 10 square meshes to the lineal inch. This last condition only obtains in the United States of America. (*Tech. Dict. Road Terms. Perm. Inter. Assoc. Road Congresses.*)

(2) A naturally occurring mixture of gravel and sand, containing sufficient clay to hold the mixture together when rolled. (B.S.892 : 1954.)

LOAM. Soil consisting of a natural mixture of clay, sand and silt. (B.S.892 : 1954.)

MADE GROUND. Ground the level of which has been raised by filling. (B.S.892 : 1954.)

OVERBURDEN. The soil or superficial material overlying the rock, gravel or sand to be extracted or the material above a specified level in the ground. (B.S.892 : 1954.)

PEBBLE. (1) A naturally eroded derivative of consolidated rock with greatest length not less than 4 mm. ($\frac{1}{4}$ in.) or more than 65 mm. ($2\frac{1}{2}$ in.). (Based on C. K. Wentworth's classification.)

(2) Rock particles of diameter greater than 2 mm. (P. G. H. Boswell's classification.)

(3) A rounded or subangular stone of relatively small size. (B.S. 892 : 1954.)

PITCHING. Large stones, usually between 7 in. and 12 in. in depth, placed by hand and compacted by rolling, with small stones or other material in the interstices, so as to form a stable base for a road. (B.S.892 : 1954.)

PITCH MASTIC. An alternative to mastic asphalt based on coal tar pitch binder. (B.S.S.1177: 1944; 1310: 1950; 175: 1947; 1450: 1948; 1783: 1951).

PIT-RUN GRAVEL. The material as obtained from a natural deposit of gravel without separation. (B.S.892 : 1954.)

QUARRY FINES. Broken stone, as crushed, which passes through the smallest screen or aperture. (B.S.892: 1954.) *Note.*--- Sometimes referred to as 'tailings'.

REJECTS. Uncrushed gravel, or broken stone or slag, which is too coarse to pass the largest screen aperture. (B.S.892 : 1954.) *Note.* --- Often referred to as 'oversize'.

RUBBLE. (1) An accumulation of angular rock and/or artificial stone fragments of entirely ungraded character and heterogeneous composition. (H.B.M.)

(2) Material consisting of stone, broken brick, or the like used as a hardcore or to provide a stable or permeable filling. (B.S.892 : 1954.)

SAND. (1) A loose detrital sediment composed substantially of quartz grains (SiO_2) in which the grade size 0.1 mm. (0.004 in.) to 2 mm. (0.08 in.) predominates. (Based on P. G. H. Boswell's classification.)

(2) (a). Small mineral particles from natural sources, usually regarded as being of such a size that all will pass an appropriate sieve¹,

¹ $\frac{3}{16}$ in. for concrete. $\frac{1}{8}$ in. for bituminous materials, No. 7 B.S. for soils. (B.S.892 : 1954.)

and free from appreciable amounts of clay and silt. The word 'sand' should be qualified by one indicating its source of origin, *e.g.* 'quarry', 'pit', 'river', etc.

(b) In the particle size analysis of soils: mineral particles of the size between 2.0 mm. and 0.06 mm.

SAND, COARSE. A loose detrital sediment composed substantially of quartz grains (SiO_2) in which the upper limit is 2 mm. (0.08 in.) and the lower limit 0.5 mm. (0.02 in.). (Based on P. G. H. Boswell's classification.)

SAND, FINE. A loose detrital sediment composed substantially of quartz grains (SiO_2) in which the upper limit is 0.1 mm. (0.004 in.) and the lower limit is 0.05 mm. (0.002 in.). (Based on P. G. H. Boswell's classification.)

SAND, MEDIUM. A loose detrital sediment composed substantially of quartz grains (SiO_2) in which the upper limit is 0.5 mm. (0.02 in.) and the lower limit is 0.25 mm. (0.01 in.). (Based on P. G. H. Boswell's classification.)

SHINGLE. (1) A term applied to water-worn, shore-line gravel (*q.v.*). Substantially free from sand (*q.v.*). (H.B.M.)

(2) Loose detritus of coarser grades than those of gravel, *e.g.* having a majority of the pebbles of a larger size than a walnut. (A. Holmes, *Nomenclature of Petrology.*)

N.B.—The definition (2) in part overlaps that of 'cobble' (*q.v.*).

(3) The term 'shingle' is taken as meaning all stones retained on $\frac{1}{2}$ in. mesh. (*B.S.A.T.A. Bulletin*, No. 1, 1936, p. 10.)

(4) Rounded or water-worn stones of irregular size and shape (as occurring in open beach formation) and substantially free from sand. (B.S.892 : 1954.)

SILT. (1) A loose detrital sediment in which the grade size from 0.01 mm. (0.0004 in.) to 0.1 mm. (0.004 in.) predominates. (Based on P. G. H. Boswell's classification.) *N.B.*—The term is often applied to a 'sandy clay'. For purposes of testing aggregates for suitability for use in concrete it is usual to regard that portion of the aggregate which can be washed through a 200 mesh B.S. sieve (aperture 0.076 mm.) as 'clay and silt'. (*A.S.T.M.*, D. 136-28.)

(2) (a) Mineral particles naturally deposited as sediment in water and usually regarded of such a size that all will pass a No. 200 B.S. sieve, and free from appreciable amounts of clay.

(b) In the particle-size analysis of soils: mineral particles of a size between 0.06 mm. and 0.002 mm. (B.S.892 : 1954.)

SILT FRACTION. That fraction of a soil composed of particles between the sizes 0.06 mm. and 0.002 mm. The silt fraction may be subdivided as follows:

Coarse silt: 0.06 mm.—0.02 mm.

Medium silt: 0.02 mm.—0.006 mm.

Fine silt: 0.006 mm.—0.002 mm.

(B.S.892 : 1954)

SLAG. The stony product resulting from metallurgical processes. The origin of the slag should be indicated by a prefix, *e.g.* blast-furnace, steel, etc. (B.S.892 : 1954.)

For the rest, modern building research covers an ever-widening field of investigation in which in increasing directions petrographic methods are invoked with great technical advantage. It is, after all, translation of results of such research in terms of everyday procedure in building construction and maintenance that constitutes the essential role of the technologist in this great industry; anything sedimentary petrography can contribute to closer understanding of building materials, whether in raw or synthesized form, continues to be of the greatest possible economic value.

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CEMENT AND CONCRETE TECHNOLOGY

Under this heading is grouped a number of artificially prepared materials widely used in building, highway engineering and allied constructional projects, embracing such raw materials and products as are described below. It will readily be appreciated that this technology is a department of applied science long established in its own right; both theoretical and practical aspects of the subject still continue to be the basis of an ever-increasing schedule of international research and application. Here, obviously, only the briefest outline of principles, technique and trends can be sketched in for the benefit of the student of sedimentary petrography. The selected bibliography will, it is hoped, prove a helpful introduction to the ramifications of the study of cement and concrete.

Firstly, some definitions:

CEMENT. 'A material which, if added in a suitable form to a non-coherent assemblage of particles, will subsequently harden by physical or chemical means and bind the particles into a coherent mass.' (B.S.892 : 1954.)

CONCRETE. 'A mixture of mineral aggregate with a cementing agent which, on chemical or temperature change, binds the whole into a solid mass. When no cementing agent is specified, the use of a cement of Portland cement type is generally understood.' (B.S. 892 : 1954.)

Next, the principal *naturally* occurring rock-types utilized as raw materials in manufacture of cement and concrete (*excluding aggregates* already described under Building Technology (p. 525)), may be tabulated as follows:

Bauxite.
'Cement Rock' (argillaceous limestone, *e.g.* Lehigh, Pa., U.S.A.).
Chalk.
Clay.
Diatomite.
Dolomite.
Gypsum.
Limestone.
Magnesite.
Marl.
Mud (Alluvial).

Pozzolana (Pozzuoli, Italy and elsewhere).
Santorin Earth (Santorin, Greece).
Shale.
Trass (volcanic tuff, Eifel).

Each of the above, as natural rock, is capable of petrological analysis along conventional lines to assist determination of impurities and interpretation of chemical analyses prior to selection, blending and use. The following is a list of the chief products manufactured from one or more of the above ingredients, together with their brief definitions:

AIR-ENTRAINING CEMENT. 'Portland, or Portland blastfurnace, cement to which a small amount of an air-entraining agent has been added during grinding.' (F. M. Lea, 1956.)

ANHYDRITE PLASTER. 'Anhydrite is the naturally occurring mineral anhydrous calcium sulphate, CaSO_4 ; anhydrite plaster is made therefrom by grinding to a powder with the addition of suitable accelerators of set.' (B.S.1191 : 1955.)

ANHYDROUS GYPSUM-PLASTER. 'The term anhydrous gypsum-plaster shall mean those plasters which consist essentially of anhydrous calcium sulphate, CaSO_4 , produced by dehydration of gypsum, by heat or other means, the set of which has been suitably accelerated.' (B.S.1191 : 1955.)

ALUMINOUS CEMENT (*e.g. Ciment Fondu*). See under High Alumina Cement.

FAT (HIGH CALCIUM) LIMES. '... obtained from the calcination of lime-stones of a high degree of purity and contains 95% and upwards of calcium oxide. On the addition of water they slake rapidly with the evolution of much heat, the lumps breaking down to form a lime putty.' (F. M. Lea, 1956.)

FERRARI CEMENT. '... a Portland cement with, originally, a ratio of alumina to iron oxide of 0.64, but now often approaching unity, and having improved resistance to chemical attack. It falls in the class of sulphate-resisting Portland cements.' (F. M. Lea, 1956.)

GYPSUM PLASTERS. 'Materials consisting essentially of calcium sulphate that are produced by the partial or complete dehydration of gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.' (F. M. Lea, 1956.)

HEMIHYDRATE. 'The term hemihydrate shall mean an intermediate phase in the dehydration of gypsum by heat or other means wherein the amount of combined water corresponds approximately to the formula $2\text{CaSO}_4 \cdot \text{H}_2\text{O}$, calcium sulphate hemihydrate.' (B.S.1191 : 1955.)

HIGH ALUMINA CEMENT. 'A hydraulic cement made by heating to a high temperature a mixture of alumina-bearing materials and limestone, and grinding the resulting fused product to a fine powder.' (B.S.915 : 1947 and amendments and B.S.892 : 1954.)

HYDRATED LIME (SLAKED LIME). Calcium hydroxide made by the action of water on quicklime.

HYDRAULIC CEMENT. 'A cement which will harden by hydration even in the presence of excess water.' (B.S.892 : 1954.)

HYDRAULIC LIMES. '... obtained from the burning of limestones containing a proportion of clay.' (F. M. Lea, 1956.)

KEENE'S AND PARIAN. 'The term "Keene's" or "Parian" shall be applied to those gypsum-plasters of the anhydrous class which are characterized by being more easily brought to a smooth and true finish in a continuous plastered surface, this property being associated as well with a slow and gradual set.' (B.S.1191 : 1955.)

KÜHL CEMENT. '... a Portland cement of low silica and high alumina and iron oxide content that has been made in a number of European countries and Japan. In strength it corresponds to rapid-hardening Portland cement.' (F. M. Lea, 1956.)

LIME CONCRETE. 'Concrete in which the cementing agent is burnt and ground lime.' (B.S.892 : 1954.)

LOW HEAT PORTLAND CEMENT. '... a material in which the chemical composition has been so adjusted as to reduce the heat of hydration. Its rate of strength development, though not its ultimate strength, is lower than that of ordinary Portland cement.' (F. M. Lea, 1956, and B.S.1370 : 1958.)

MAGNESIUM OXYCHLORIDE OR SOREL CEMENT. '... the product obtained when magnesia and a solution of magnesium chloride react together.' (F. M. Lea, 1956.)

ORDINARY PORTLAND CEMENT. 'A hydraulic cement made by heating to a high temperature a mixture of clay and limestone, and grinding the resulting clinker to a fine powder.' (B.S.12 : 1958 and B.S.892 : 1954.)

PLASTER OF PARIS. 'The term plaster of Paris shall mean a form of hemihydrate without any added retarder of set. It is manufactured in several grades for various industrial uses.' (B.S.1191 : 1955.)

PORTLAND BLASTFURNACE CEMENT. 'A cement made by grinding granulated blastfurnace slag and Portland cement clinker together to a fine powder.' (B.S.146 : 1958, and B.S.892 : 1954.)

PORTLAND CEMENT CONCRETE. 'Concrete in which the cementing agent is Portland cement.' (B.S.892 : 1954.)

POZZOLANIC MATERIAL. 'A naturally occurring or artificial siliceous material which has no cementing properties in itself, but which will combine with free lime or with Portland cement in the presence of water at ordinary air temperature to form a material having cementing properties. Sometimes used as an addition to Portland cement.' (B.S.892 : 1954.)

PRE-STRESSED CONCRETE. 'Concrete in which tensile stress, under given conditions of loading is eliminated or reduced to safe limits, by the imposition of permanent compressive forces of predetermined magnitudes and directions.' (B.S.892 : 1954.)

QUICKLIME. Calcium oxide made by calcining limestone (calcium carbonate).

QUICK-SETTING PORTLAND CEMENT. 'A Portland cement made in such a way that its initial setting time is substantially less than that of ordinary Portland cement.' (B.S.892 : 1954.)

RAPID HARDENING PORTLAND CEMENT. 'A Portland cement which by adjustment of its chemical composition and grinding to a finer powder, has the property of attaining a specified strength in a relatively short time after setting.' (B.S.12 : 1958, and B.S.892 : 1954.)

REINFORCED CONCRETE. 'Concrete in which rods, bars or fabric usually of steel are embedded for the purpose of resisting particular stresses.' (B.S.892 : 1954.)

RETARDED HEMIHYDRATE GYPSUM PLASTER. 'The term retarded hemihydrate shall mean a form of hemihydrate which contains an addition of a retarder of set.' (B.S.1191 : 1955.)

SLAG CEMENT. '... cold process slag cement ... is a mixture of hydrated lime and granulated blastfurnace slag.' (F. M. Lea, 1956.)

SULPHATE-RESISTING CEMENT. '... a material with a composition so adjusted as to give it an increased resistance to sulphate-bearing waters.' (F. M. Lea, 1956.)

SUPERSULPHATED CEMENT. '... composed essentially of granulated blastfurnace slag, calcium sulphate and a small percentage of Portland cement or lime.' (F. M. Lea, 1956.)

WATERPROOFED PORTLAND CEMENT. '... ordinary Portland cements to which has been added in grinding a small proportion of calcium stearate or of a non-saponifiable oil.' (F. M. Lea, 1956.)

WHITE PORTLAND CEMENT. 'Is an ordinary Portland cement containing only a low proportion of iron oxide, so that its colour is white instead of grey.' (F. M. Lea, 1956.)

These several cements, in conjunction with different aggregates, e.g. sand, gravel, limestone, igneous rock, slag, etc., p. 529, enter into the design of ultimate products known to builders, civil engineers and many other professions and trades, as concrete, mortar, plaster, and so on. Thus petrographic investigations in this technology concern not only fundamental raw materials, but also various cements manufactured therefrom and finally the characteristic products into which they enter. With the raw materials, we are not here concerned because they have received ample treatment in other chapters in this volume. In so far as petrographic studies of cementing materials *per se* are concerned, however, the technique is vastly different and highly specialized. The problems involved have engaged an international body of cement chemists, petrographers and physicists, ever since the

pioneer days of H. Le Chatelier¹ and A. E. Törnebohm², who may be said to have laid the foundations of cement microscopy. (See bibliography at the end of this section for other and more modern authors in the literature of this subject.)

Le Chatelier's chief contribution at the time was the identification of tricalcium silicate as the main component of Portland cement clinker and to which he ascribed the cementing qualities of this material when finely ground. Törnebohm's work extended this diagnosis in recognizing five distinct constituents to which he gave the names 'alite', 'belite', 'celite', 'felite' and an isotropic residue. Although these terms have, to a large extent, been discarded as unscientific and therefore worthless, they still appear in the literature of cement, unfortunately often with different meanings. Actually, more recent studies of Portland cement clinker indicate that the essential compounds entering into its composition are silicates, aluminates and ferrates. One interpretation is that 'alite' corresponds to tricalcium silicate ($3\text{CaO} \cdot \text{SiO}_2$), 'belite' to β -dicalcium silicate, 'celite' to $4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$ solid solution, and 'felite' to calcium aluminate; the 'isotropic residue' is probably isometric tricalcium aluminate and some glass³.

In the microscopical examination of cement clinker and cement powder in transmitted light, two methods of approach are normally followed, via thin section and/or powder mounts. In the case of thin section preparation, water must obviously be avoided as a grinding medium because of possibility of cement hydration. Among the media employed are absolute alcohol, glycerin, white spirit, paraffin and ethylene glycol. Where the clinker is porous or friable, resin impregnation is necessary prior to grinding (see Vol. I, p. 94). The procedure for cutting thin sections should follow conventional methods for rock-slices, except that use of 60-min. carborundum for coarse grinding, 120-min. carborundum for medium grinding and finishing with 4F carborundum, is recommended. Some workers prefer to use emery as the abrasive, also a resin of relatively high R.I. (1.71) as mountant rather than Canada balsam⁴. Thin sections must be *really thin*, not more than 20μ , a thickness at which tricalcium silicate exhibits characteristic greyish-white polarization colours.

With powder mounts, cement clinker must be finely ground. Microscopical examination alone is by no means always conclu-

¹ *Experimental Researches on Constitution of Hydraulic Mortars* (McGraw-Hill, New York), 1905 (translated by J. L. Mack).

² *Tonind.-Zeitung*, 21, 1897, p. 1148; *Baumaterialienkunde*, 6, 1910-11, p. 142; *Zement*, 4, 1903, p. 287.

³ See also H. Insley and Van Derck Fréchette, *Microscopy of Ceramics and Cements, etc.* (Academic Press, New York), 1955, Ch. 10, p. 177.

⁴ H. Insley and Van Derck Fréchette, *op. cit.*, p. 178.

sive, owing to the inherent difficulty of determining, by optical means alone, identity of finely divided particles of the different components.

Most cement minerals have relatively high refractive indices, consequently R.I. determinations by immersion methods where employed in diagnosis, require the use of specially selected media, e.g. methylene iodide (1.737–1.741); methylene iodide sulphur mixture (1.778); methylene iodide, sulphur and iodide mixture (1.868); sulphur-selenium mixture (1.998); and selenium-arsenic-selenide mixture (2.72–3.17) (see Vol. I, Ch. VI, p. 249). This is not, however, the complete answer to some of the difficulties involved.

It is also possible to study and interpret polished thin sections, or polished flat-surface sections of cement clinker by metallurgical procedure plus etching, implying examination by reflected light. This is the most modern technique and has largely replaced thin section study except where precise optical determinations are required. Details of polishing and etching methods are given by F. M. Lea¹.

In certain cases X-ray diffraction methods are available² and the possibilities of the electron microscope cannot be overlooked³.

The following brief descriptions of some of the important constituents of Portland cement may prove helpful to the student of this subject.

CALCIUM ORTHOSILICATE ($2\text{CaO} \cdot \text{SiO}_2$). Identified in four forms: α , α' , β , γ . $\alpha 2\text{CaO} \cdot \text{SiO}_2$: ? hexagonal; R.I. 1.70–1.71; uniaxial +; density 3. $\alpha 2\text{CaO} \cdot \text{SiO}_2$ (*bedigite*): ? monoclinic; R.I. 1.71–1.73; biaxial -; $2V = 20^\circ\text{--}30^\circ$; density 3.4. $\beta 2\text{CaO} \cdot \text{SiO}_2$ (*larnite*): monoclinic; striations due to twinning characteristic; R.I. 1.71–1.75; biaxial -; $2V$ moderate or large; density 3.3. $\gamma 2\text{CaO} \cdot \text{SiO}_2$: colourless, prismatic, prismatic cleavage; straight extinction; R.I. 1.64–1.65; biaxial -; density 3.

TRICALCIUM SILICATE ($3\text{CaO} \cdot \text{SiO}_2$). Colourless; granular; without cleavage; may be fibrous; lamellar twinning; small extinction angle; R.I. 1.71–1.72; uniaxial -; birefringence weak, < 0.005 ; optic axial angle variable; density 3.2. The main cementing agent in Portland cement.

TRICALCIUM ALUMINATE ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$). Colourless; occasionally crystalline; isometric; poor cleavage || (111) or (110); R.I. 1.71; $H = 6$; density 3.04. There are many other forms of the system $\text{CaO--Al}_2\text{O}_3$, but this constituent occurs in Portland cement⁴.

¹ *The Chemistry of Cement and Concrete* (Arnold, London), 1956.

² H. G. Midgley, Symposium (London), 1952.

³ F. M. Lea, *op. cit.*, pp. 220, 267.

⁴ F. M. Lea, *op. cit.*, p. 52.

'BROWNMILLERITE' ($4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$). Reddish-brown; prismatic grains; R.I. $\alpha = 1.96$, $\beta = 2.01$, $\gamma = 2.04$; biaxial —; 2V small; density 3.77; pleochroic, γ = brown, α = yellow. There is a doubt whether this constituent is of definite composition; it may represent a special phase in a solid solution series¹.

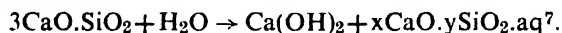
CALCIUM OXIDE (CaO). Difficult of identification in clinker, where it occurs either as minute spherical particles, interstitially, or as inclusions in tricalcium silicate or tricalcium aluminate. In crystalline state is isometric, hence isotropic, but according to H. Insley and Van D. Fréchette, never found in Portland cement clinker with crystal faces². For identification in finely powdered cement or clinker, White's test is available³; in polished clinker specimens, water-etching is indicative⁴. $H = 3.4$; S.G. = 3.32; R.I. 1.833–1.846. Colourless. Its presence in clinker is generally indicative of excess CaO in composition due to incomplete reaction with silicates, etc., during burning.

PERICLASE (MgO). Colourless; cubes, octahedrons and grains; perfect cleavage $\parallel (100)$, imperfect $\parallel (111)$; isometric; $H = 5.5$; S.G. = 3.58. R.I. 1.734–1.737. In clinker, often occurs in angular, octahedral grains interstitially. It is best recognized in unetched polished specimens by reflected light where its relatively great hardness makes it stand out in relief.⁵

GLASS. Is variable in composition and always interstitial. Frequently difficult of identification by transmitted light in presence of other isotropic constituents. Devitrification sometimes happens and produces silicates, aluminates, etc. R.I. of glass varies with composition; with low $\text{Al}_2\text{O}_3 : \text{Fe}_2\text{O}_3$ ratio R.I. is > 1.72 ; with high $\text{Al}_2\text{O}_3 : \text{Fe}_2\text{O}_3$ ratio, R.I. tends to be < 1.72 . For identification in polished clinker sections, see ref. 6 below.

The petrographic study of Hydrated Portland Cement is more difficult and this technique *alone* has limitations. X-ray diffraction, electron diffraction, electron microscopy, often coupled with chemical analysis, combine, perhaps, a more modern approach to the problems involved. Obviously mineral compounds in Portland cement *per se* are anhydrous; it is their individual and collective reaction to water which determines the nature of hydrated compounds thus formed, hence setting and hardening characteristics of the ultimate product.

Basically, the reaction involved may be demonstrated by the following equation:



¹ F. M. Lea, *op. cit.*, p. 58.

² *Op. cit.*, p. 186.

³ *Op. cit.*, p. 187.

⁴ *Op. cit.*, p. 187.

⁵ *Op. cit.*, p. 187.

⁶ H. Insley and Van Derck Fréchette, *op. cit.*, p. 190.

⁷ F. M. Lea, *op. cit.*, p. 169.

Of these products, CALCIUM HYDROXIDE $\text{Ca}(\text{OH})_2$ tends to form in colourless hexagonal, platy crystals, with perfect basal cleavage; R.I. low, $\omega = 1.574$, $\epsilon = 1.545$; birefringence strong, $\omega - \epsilon = 0.029$; optically uniaxial -. The calcium silicate hydrate is usually microscopically amorphous.

The work of M. Swerdlow and others¹ has recently revealed by electron microscopy that, with complete hydration of tricalcium silicate, also of Portland cement, extremely finely divided particles or clusters, with diameters 50–200 Å, are formed, having crystalline and optical characteristics of the natural mineral *Afwillite* ($3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$); this is monoclinic, prismatic, with perfect (001) and imperfect (100) cleavages; R.I. high, $\alpha = 1.6169$, $\beta = 1.6204$, $\gamma = 1.6336$; birefringence very strong, $\gamma - \alpha = 0.0167$. Optically biaxial -; $2V = 54^\circ 40'$.

Hydration of tricalcium aluminate produces two forms, initially hexagonal platy crystals and, with time, degeneration into isometric² crystals in characteristic hexakis octahedra ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$).

Tricalcium aluminoferrite ('Brownmillerite'), ($4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$) hydrates to form hexagonal platy crystals of hydrated tricalcium aluminate together with segregation of a hydrated ferric oxide compound which appears to be amorphous. Ultimately the hexagonal plates appear to break down into the isometric form $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$. This reaction is complex and probably not yet completely resolved in its mechanism³.

The influence of the presence of *Gypsum* ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) does not appear to effect hydration of the di- and tri-calcium silicate components, but it does definitely influence the reaction of tricalcium aluminate; in this instance the end product appears to be *Calcium Sulphoaluminate* ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O}$) in a characteristic hexagonal, acicular form; long needles with low R.I. $\omega = 1.464$, $\epsilon = 1.458$, birefringence low, $\omega - \epsilon = 0.006$, optically uniaxial -. Although this product may be of normal occurrence in set Portland cement, the reaction recalls the hazard of attack of sulphate-bearing waters on Portland cement concrete.

Portland Blastfurnace Cement or Portland-Slag Cement is a mixture of ordinary ground Portland cement clinker and granulated slag. 'These two materials may be mixed together in such proportions as the manufacturer may prefer, subject to the proviso that in no case shall the proportion of slag exceed 65 per cent by weight of the total quantity'⁵. Petrographic procedure is in accordance with that laid down for Portland cement (above) and the technique of slag microscopy also enters into the problem⁶.

¹ M. Swerdlow, H. F. McMudie and F. A. Heckman, *Proc. Intern. Conf. on Electron Microscopy* (London), 1954.

² F. M. Lea, *op. cit.*, p. 172 and Pl. V(i).

³ L. S. Wells, W. F. Clarke and H. F. McMudie, *Journ. Research Nat. Bur. Standards*, 30, 1943, pp. 367–409.

⁴ H. Insley and Van Derck Fréchette, *op. cit.*, p. 196.

⁵ B.S.146: 1958, p. 5. ⁶ B.S.1047, 1952.

The petrographic study of High Alumina Cement Clinker ('Ciment Fondu' or 'fused cement') again presents complex problems in interpretive microscopy. The reactive compounds in this type of cement appear to be 'unstable $5\text{CaO} \cdot 3\text{Al}_2\text{O}_3$, $\text{CaO} \cdot \text{Al}_2\text{O}_3$ and $\text{CaO} \cdot 2\text{Al}_2\text{O}_3$ '. The petrographic examination of thin sections of high alumina cement has confirmed that these compounds do occur although the structure of the clinker is such that identification of minerals is often not easy by this method. In addition, the appearance under the microscope shows much more variability from one clinker to another, or even between different parts of the same clinker, than is common with Portland cement clinker. It is accordingly more difficult to describe a characteristic appearance².

'UNSTABLE $5\text{CaO} \cdot 3\text{Al}_2\text{O}_3$.' This may actually be $6\text{CaO} \cdot 4\text{Al}_2\text{O}_3 \cdot \text{FeO} \cdot \text{SiO}_2$.³ Recognized by elongated, prismatic (lath-shaped) crystals, R.I. high, $n = 1.69$, birefringence low (about 0.005); strong pleochroism, blue-violet \parallel to length, colourless \perp to length.

MONOCALCIUM ALUMINATE ($\text{CaO} \cdot \text{Al}_2\text{O}_3$). Orthorhombic or monoclinic; prismatic; cleavage strong \parallel (110). Pseudo-hexagonal twinning on (130) or polysynthetic. R.I. high, $\alpha = 1.643$, $\beta = 1.655$, $\gamma = 1.663$; birefringence moderate, $\gamma - \alpha = 0.020$; optic axial plane (010); $X = c$; optically biaxial $-$; $2V = 36^\circ$.

$\text{CaO} \cdot 2\text{Al}_2\text{O}_3$. Probably tetragonal; crystals elongated (lath-shaped) but sometimes in rounded grains; R.I. high, $\omega = 1.617$, $\epsilon = 1.652$; birefringence strong, $\epsilon - \omega = 0.035$; optically uniaxial $+$. This compound was once thought to have optical properties consistent with the compound $3\text{CaO} \cdot 5\text{Al}_2\text{O}_3$ (tricalcium pentaluminate)⁴.

GEHLENITE ($2\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{SiO}_2$). According to N. Sundius⁵, this mineral is commonly present in aluminous cement but does not appear to have cementing properties. Tetragonal, prismatic; colourless; poor cleavage \parallel (001) and (110). R.I. high, $\omega = 1.669$, $\epsilon = 1.658$; birefringence moderate, $\omega - \epsilon = 0.011$; optically uniaxial $-$; weak pleochroism, yellow-brown-greenish blue (not always observed in the synthetic product). $2\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{SiO}_2$ glass has a lower R.I., $n = 1.638\text{Na}$.

The petrographic examination of Concrete and Cement Mortars differs from the foregoing techniques described for Portland cement clinker, etc., in that account must necessarily be taken of the type of aggregate employed. Aggregates vary considerably in composition according to whether the concrete is 'heavy' (density

¹ H. Insley and Van Derck Fréchette, *op. cit.*, p. 198.

² F. M. Lea, *op. cit.*, p. 432.

³ T. W. Parker, *Proc. 3rd Inter. Symposium on the Chemistry of Cement, Cement and Concrete Assoc.* (London), 1952, pp. 485-514.

⁴ G. A. Rankin and F. E. Wright, *Amer. Journ. Sci.*, **39**, 1915, pp. 1-79.

⁵ Symposium on Chemistry of Cements, *Ing. Vetenskaps Akad.* (Stockholm), 1938, pp. 395-421.

140–150 lb./cub. ft.) or 'light' (density 40–100 lb./cub.ft.). The following is a classification of the most common types of aggregate employed:

'HEAVY'	'LIGHT'	
Blastfurnace slag	Asbestos	Pumice
Brick (crushed)	Clay (expanded)	Shale (expanded)
Gravel	Clinker	Slag (foamed)
Rock (crushed)	Fly-ash	Slate (expanded)
Sand	Perlite (expanded)	Vermiculite (exfoliated)

Of the 'heavy' types, blastfurnace slag, gravel (*i.e.* + $\frac{3}{8}$ in.), crushed rock (*e.g.* basalt, limestone), and silica sand (*i.e.* – $\frac{3}{8}$ in.), are most commonly employed; each is readily identified in thin sections of concrete by normal petrographic procedure.

Of the 'light' types, asbestos enters into manufacture of asbestos-cement products (*e.g.* sheets, corrugated roofing, pipes, etc.); clinker, foamed slag and fly-ash (pulverized fuel-ash) are common components; perlite (a volcanic glass) and pumice (likewise of volcanic origin) are locally employed, especially where such materials are readily available.

Expanded clays, shales and slates are products of fusion of certain special types prone to 'bloating' (*i.e.* swelling) when heated; they are not universally popular and, like vermiculite, are generally only employed in special circumstances. Here again petrographic methods of identification should present no difficulty, except possibly in the case of the expanded products. 'Bloomed' slates, when examined microscopically, show partial or complete destruction of the carbonate minerals calcite and dolomite, and the formation of considerable interstitial glass¹. Frequently circular cells in vitrified minerals ('gas-holes') are a clue to the presence of bloated aggregates of this kind.

Cement Mortars frequently present problems in diagnosis mainly on account of the relatively small size of the aggregate particles. Much the same may be said of Plasters. A prior knowledge of exactly what ingredients have been employed is, of course, always helpful. Much may be done in these cases by first eliminating the binder (*e.g.* cement, gypsum, etc.) and then proceeding with a microscopical examination of the residual material along conventional lines.

Collateral chemical analysis of samples of mortar or plaster is often of considerable assistance in interpreting microscopical data, especially where the problem in hand is one of cause of failure. This remark applies equally and with possibly more force to investigation of concrete failure. The microscope provides the qualitative evidence while chemical analysis not only is confirmatory but

¹ H. Insley and Van Derck Fréchette, *op. cit.*, p. 207.

quantitative. Calculations, incidentally, soon disclose what are the actual mix proportions present, hence whether the materials do, in fact, meet specified requirements.

Before concluding this section, mention should be made of a particular type of concrete failure caused by reactivity of certain aggregate components with alkaline constituents of Portland cement. Chemical analysis usually discloses less than 1% of combined K_2O and Na_2O , but with some rock-types, e.g. volcanic glass, rhyolite, andesite, trachyte, and dolerite containing the mineral *chlorophaeite* (one of the chlorite group), this may be quite sufficient to cause expansion of concrete and consequent failure. This subject has already been dealt with¹, but the interested reader will do well to consult further references below².

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² H. Insley and Van Derck Fréchette, *op. cit.*, p. 205.

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CERAMICS

Fundamentally the ceramic industry is concerned with the 'plastic art' of mixing, moulding or shaping, then burning, clay in the manufacture of earthenware, pottery, porcelain, porcelain enamel, whiteware and similar products. Both in technology and commercial activities, relationship with the refractories industry (p. 577) is close, while many building materials are fabricated from raw substances and so processed as to bring them well within the category of ceramic products.

The aid which sedimentary petrography affords in the technology of ceramic products is two-fold; investigation of raw materials and microscopy of synthetic bodies produced therefrom. The former involves normal and relevant petrographic methods; but microscopical investigation of fired products is a different matter altogether, involving specialist knowledge of processes, conditions of firing, mineral conversions and inversions, and recognition by various means of complex synthetic silicates, etc., entering into their constitution.

The raw materials employed in this industry are geologically and mineralogically varied, both as regards nature and origin. They comprise not only specially selected natural potters' clays and minerals, but also fluxes, stains for glazing, pigments, etc. Of natural rocks and minerals employed, the following list comprises the most important; an indication is also given of some of the uses to which such raw materials are normally put.

SUBSTANCE	PURPOSE
Andalusite (calcined)	High temperature bodies.
Ball clay	Porcelain, earthenware.
Bauxite	Source of alumina.
Ceramic talc (steatite)	Wall-tile bodies, high-frequency insulation.
China clay	White china-ware, sanitary goods, electrical porcelain.
China stone	Porcelain, earthenware.
Cordierite	Insulators.
Felspar	Flux.

SUBSTANCE	PURPOSE
Fireclay	Sanitary tiles, saggars, cylinder liners, pavors, etc.
Flint	Source of amorphous silica.
Fluorspar	Flux.
Gypsum	Moulds for casting ceramic ware.
Kaolin	Porcelain.
Kyanite (calcined)	High-temperature bodies, sparking plugs, etc.
Magnesite	Source of magnesia.
Mullite (synthetic from sillimanite)	High-temperature bodies.
Nepheline-syenite	Flux.
Pegmatite	Source of felspar.
Pyrophyllite	Wall-tile bodies.
Quartz	Source of silica.
Sillimanite (calcined)	High-temperature bodies, sparking plugs, etc., added to clay and kaolin to reduce shrinkage, increase breaking strength, extension of sintering range.
Spodumene	Pottery bodies.
Titanium oxide	Whitening agent.
Whiting (prepared from chalk)	China-ware.

Petrological examination of raw materials has for its chief end determination of mineral composition as an aid to interpreting chemical analyses; it is particularly valuable in recognizing impurities or deleterious compounds considered from the standpoints of firing cycle and ultimate product.

In investigating fired bodies, a number of vital characteristics may be determined with the aid of a petrological microscope *alone*, although today recourse to chemical analysis, electron microscope, physical measurements, spectrographic, X-ray diffraction techniques, etc., is the rule rather than the exception, especially in difficult diagnosis. Among characteristics commonly sought by petrographic methods *per se*, are the following:

- (a) Uniformity or otherwise of grain-size (texture).
- (b) Particle-size range (micron analysis).
- (c) Structure (type of crystallization achieved, *e.g.* mutual interference; fibrous; punctate; porphyritic; granular, etc.).
- (d) Artificial mineral composition (fired products).
- (e) Degree of conversion or inversion of original natural minerals or raw materials.
- (f) Presence or absence of glass.

In regard to (a), (b) and (c), no difficulty normally arises from a petrographic standpoint. In the matter of identification of synthetic ceramic minerals produced as a result of firing (d), this is rather

a different story, calling for both experience and specialist knowledge; much the same thing may be said regarding conversion and inversion phases (*e*). No difficulty should arise in diagnosis of glass (*f*), but confirmatory tests are in certain cases available.

Let us consider briefly some of the more important *artificial minerals* which contribute commonly to the end-products of ceramic manufacture. The student first attempting a study of these minerals will find that the best way of starting is to acquire some thin sections, also mounts of corresponding incoherent mineral grains, also similar powders for R.I. determinations in appropriate liquids, in some or all of the compounds listed and annotated below. Each object must be studied intensively as regards its optical properties, refractive indices and specific gravities. With experience the series should be extended to include other synthetic minerals, also variants from different sources and products. Naturally occurring examples of minerals such as cristobalite, tridymite, etc., should be procured to compare with their synthetic counterparts. Variations in physical and optical characteristics will be noted and recorded as a basis of reference in future work and thus a collection of ceramic 'microscopic objects' accumulated which is invaluable in this field of research, as it certainly is in practical application. The data summarized below are arranged for convenience in alphabetical order.

LIST OF NATURAL AND SYNTHETIC MINERALS FOUND IN CERAMIC MATERIALS¹

α -ALUMINA (CORUNDUM) (α - Al_2O_3). Trigonal. (0001) plates. S.G. 4. R.I. very high, $\omega = 1.768$ $\epsilon = 1.760$. Birefringence weak, $\omega - \epsilon = 0.008$. Optically uniaxial —. M.P. 2,050°–2,080°C. *Source*: fused alumina bricks; aluminous firebricks; some laboratory ware; sparking plugs; insulators.

β -ALUMINA ($11\text{Al}_2\text{O}_3 \cdot \text{Na}_2\text{O}$). Hexagonal. Triangular plates. S.G. 3.31. R.I. high, $\omega = 1.66$ – 1.69 , $\epsilon = 1.63$ – 1.66 . Birefringence $\omega - \epsilon = 0.03$. Optically uniaxial —. Converts to α - Al_2O_3 , 1,300°C.–1,400°C. in hydrogen or vacuum. *Source*: alumino-silicate refractories.

γ -ALUMINA (γ - Al_2O_3). Isometric. S.G. 3.47. R.I. high, $n = 1.696$. Isotropic. *Source*: heated precipitated Al_2O_3 for some hours to 925°C. Product is amorphous, changes to α - Al_2O_3 on heating for 1 hour at 1,000°–1,200°C. Present in soft-fired fireclay products.

ANDALUSITE ($\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$). See Ch. I this volume, p. 39. Inverts to mullite and glass at 1,545°C.

CALCINED CHINA CLAY. Resembles calcined kyanite in optical characteristics. Acicular mullite often present.

¹ Much more detailed information on these and many other ceramic minerals will be found in the textbooks marked * in the bibliography, pp. 553, 554.

CALCINED FLINT. See Chalcedony, Ch. I, this volume, p. 73. Calcined flint is the product of heating to $1,100^{\circ}\text{C}$. S.G. 2.45. At $1,250^{\circ}\text{C}$., converts to cristobalite (*q.v.*). An important constituent of ceramic bodies.

CLINOENSTATITE ($\text{MgO} \cdot \text{SiO}_2$). Monoclinic. Square prisms or tablets. S.G. 3.19–3.28. R.I. high, $\alpha = 1.650$, $\beta = 1.654$, $\gamma = 1.660$. Birefringence moderate, $\gamma - \alpha = 0.01$. Optically biaxial +. M.P. $1,557^{\circ}\text{C}$. *Source*: Electrical porcelain based on steatite. *Note*.—Enstatite (Ch. I, this volume, p. 101) is stable below $1,140^{\circ}\text{C}$.; clinoenstatite is the high-temperature phase.

CRISTOBALITE (SiO_2). Tetragonal (below 200°C .). (Isometric above 275°C .) S.G. 2.32. R.I. low, $\omega = 1.487$, $\epsilon = 1.484$. Birefringence low, $\omega - \epsilon = 0.003$. Optically uniaxial -. M.P. $1,710^{\circ}\text{C}$. Stable above $1,470^{\circ}\text{C}$. Inverts between 200° – 275°C . *Source*: silica bricks.

DICALCIUM FERRITE ($2\text{CaO} \cdot \text{Fe}_2\text{O}_3$). Low symmetry. Crystal system uncertain. R.I. very high, $n = 2.25$. Optically biaxial +. Dissociates at $1,436^{\circ}\text{C}$. to CaO and glass. *Source*: from glass at $1,000^{\circ}$ – $1,400^{\circ}\text{C}$.; basic bricks high in lime; basic bricks reactive with iron oxide slag. **LIME** (CaO). Isometric. Rounded grains. S.G. 3.32. R.I. very high, $n = 1.838$. Isotropic. M.P. $2,570^{\circ}\text{C}$. Reversible inversion at about 420°C . *Source*: basic bricks (calcined dolomite above $1,700^{\circ}\text{C}$.) and other dolomite refractories.

KYANITE ($\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$). See Ch. I, this volume, p. 132. Inverts to mullite and glass at $1,545^{\circ}\text{C}$. Usually calcined at $1,450^{\circ}\text{C}$. before use as grog in ceramic products. May convert to mullite and cristobalite or glass at high temperature.

MONOCALCIUM FERRITE ($\text{CaO} \cdot \text{Fe}_2\text{O}_3$). Tetragonal or hexagonal. Laths or needles. S.G. 4. R.I. very high, $\omega = 2.58$, $\epsilon = 2.43$. Birefringence very strong, $\omega - \epsilon = 0.15$. Optically uniaxial -. Dissociates at $1,216^{\circ}\text{C}$. Formed from glass at $1,190^{\circ}\text{C}$. *Source*: dolomite bricks attacked by iron oxide slags.

MULLITE ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$). Orthorhombic. Laths, needles, 'square' cross-sections. S.G. 3.03. R.I. high, $\alpha = 1.642$, $\beta = 1.644$, $\gamma = 1.654$. Birefringence moderate, $\gamma - \alpha = 0.012$. Optically biaxial, +. M.P. $1,810^{\circ}\text{C}$. *Source*: porcelain bodies and glaze-porcelain interface. Fused clays.

PARAWOLLASTONITE ($\text{CaO} \cdot \text{SiO}_2$). (Modification of $\beta\text{-CaO} \cdot \text{SiO}_2$.) Monoclinic. R.I. high, $\alpha = 1.620$, $\beta = 1.631$, $\gamma = 1.633$. Birefringence moderate, $\gamma - \alpha = 0.013$. $\beta\text{-CaO} \cdot \text{SiO}_2$ stable below about $1,180^{\circ}\text{C}$. (See General References, G. R. Rigby.)

PSEUDO-WOLLASTONITE ($\alpha\text{-CaO} \cdot \text{SiO}_2$). Pseudo-hexagonal or ? monoclinic. S.G. 2.905. In equant grains with perfect basal cleavage (001). S.G. 2.905. R.I. high, $\alpha = 1.610$, $\beta = 1.611$, $\gamma = 1.651$. Birefringence strong, $\gamma - \alpha = 0.041$. M.P. $1,540^{\circ}\text{C}$. Wollastonite (*q.v.*) inverts to pseudo-wollastonite at $1,200^{\circ}\text{C}$. *Source*: silica bricks, blastfurnace slags.

QUARTZ (SiO_2). See Ch. I, this volume, p. 171. Inverts at 572°C . *Source*: firebricks, earthenware, certain porcelains.

SILICA GLASS (SiO_2). Amorphous. R.I. low, $n = 1.459$. Isotropic. May invert to cristobalite after prolonged heating above $1,000^\circ\text{C}$. *Source*: grog containing fused silica in certain fireclay products.

SILLIMANITE ($\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$). See Ch. I, this volume, p. 179. Formed from clay minerals heated above 950°C . Inverts to mullite and glass at $1,545^\circ\text{C}$.

SPINEL GROUP. See Ch. I, this volume, p. 182. Embraces aluminates, chromites and ferrites and found in slags, refractories, etc., as end-products under special conditions of mix and firing.

TRIDYMIT (SiO_2). Orthorhombic (below 117°C .). (Hexagonal above 117°C .) Lath- or wedge-shaped or arrowhead crystals. S.G. 2.26–2.28. R.I. low, $\alpha = 1.469$, $\beta = 1.470$, $\gamma = 1.473$. Birefringence low, $\gamma - \alpha = 0.004$. Optically biaxial – (below 117°C .). M.P. $1,670^\circ\text{C}$. Inverts at 117°C . and 163°C . Stable phase of SiO_2 between 870°C . and $1,470^\circ\text{C}$. Inverts to quartz below 870°C . and to cristobalite above $1,470^\circ\text{C}$. *Source*: silica bricks, siliceous bricks, used fireclay glass pots, siliceous glass.

WOLLASTONITE ($\text{CaO} \cdot \text{SiO}_2$). (Modification of $\beta\text{-CaO} \cdot \text{SiO}_2$.) See Ch. I, this volume, p. 201. Triclinic. As laths. S.G. 2.915. R.I. high, $\alpha = 1.616$, $\beta = 1.629$, $\gamma = 1.631$. Birefringence moderate, $\gamma - \alpha = 0.015$. Optically biaxial –. Inverts at $1,200^\circ\text{C}$. to $\alpha\text{-CaO} \cdot \text{SiO}_2$. *Source*: blastfurnace slags, lime-silica slags; devitrification of lime silica glass.

Microscopical examination of normal whiteware bodies based on quartz-felspar-kaolin (ball and china clays) is generally straightforward in interpretation of the fired mineral products. Much depends on firing temperature which, for the particular body under examination, should be known if possible. Of these three phases, quartz exhibits little or no change up to 1300°C . Between 1300°C . and 1400°C . fluxing produces gradual disappearance of quartz *per se* and conspicuous rounding of the large particles. Around 1425°C . quartz is absent and the fired porcelain is seen to consist principally of mullite plus glass. The felspar melting range depends on composition of the raw mineral but is generally within 1100°C .– 1250°C .; the fired product is usually isotropic, with mullite needles forming about 1250°C . The kaolin dehydrates between 500°C .– 600°C . and becomes isotropic. Over the firing range 1200°C .– 1425°C . mullite becomes progressively prominent. For details of the thermal mechanism of these transformations, see references below¹.

Petrographic methods are also of considerable value in control

¹ A. A. Klein, Constitution and Microstructure of Porcelain, *Nat. Bur. Standards (U.S.) Tech Paper* 80, 1916–17.

A. B. Peck, Effect of Time and Temperature on the Microstructure of Porcelain, *Journ. Amer. Ceram. Soc.*, 2, 1919, pp. 175–194.

H. Insley and Van Derck Fréchette, *op. cit.*, Ch. 7.

of crystalline phases, particle size and purity of components, stresses and texture, in whiteware glazes¹.

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FILLERS

From a strictly technical standpoint the essential function of a filler¹ is to occupy voids in an otherwise balanced aggregate incorporated with a fluid or semi-fluid matrix. Alternatively, fillers are employed when properly dispersed to give homogeneity and a degree of solidarity to what are initially plastic substances. Industrially filler is looked upon as a reinforcement and as a cheapening agent. It is usually an inert substance, *i.e.* one which has no chemical reaction with the medium with which it is mixed. A property common to practically all fillers employed in industry is the extremely fine state of division of the constituent particles; in a majority of cases filler is essentially — 200 mesh material containing a proportion of particles of unit micron size or less.

Fillers employed in manufacturing processes today vary greatly in mineral composition. In many cases they are by-products of rock-quarrying operations which had for long been regarded as unremunerative crusher-run 'dust', a waste material for which there was no apparent outlet. With the growth of certain key industries, however, such as plastics, rubber, asphalt, paint, etc., the demand for suitable inert fillers has greatly increased in recent years, so that practically every producer of fine 'dust' derived from both natural or artificial materials has been at pains to ascertain to what extent these presumably waste-substances could be utilized

¹ For technical definitions of the term 'filler', see p. 531.

in other industries. Considerable research has therefore been carried out on a host of raw materials and their successful employment as fillers in the several industries concerned has been one of the most remarkable testimonies to the value of modern industrial research.

The following list of materials employed as fillers in various industries today is not intended to be exhaustive; in fact it is doubtful whether any list could be regarded as final in view of the fact that so many new additions are being made from time to time, not only of natural rock powders, but also of the by-products of certain industries concerned with synthetic substances. Among the commonest fillers employed are the following:

Ashes ('Fine stuff')	Gypsum
Barite	Hydrated lime
Bauxite	Limestone dust
Bentonite	Micro-anhydrite
Carbon black	Micro-asbestos
Cement	Micro-dolomite
China clay	Micro-limestone
Clay (dried and pulverized)	Micro-talc
Clinker (ground)	Precipitated chalk
Diatomite	Rubber, disintegrated (rubber waste)
Flue dust	Slag dust
French chalk	Slate dust
Fuller's earth	Sulphur
Granite dust	Tripoli powder
Ground glass	Whiting.

It will be observed that most of the above substances are essentially naturally occurring rocks or minerals for the most part artificially rendered to a fine state of division. In nearly every case microscopical examination reveals not only purity of composition or otherwise, but also average particle size and shape, the two latter among the most important properties used to determine suitability of a specific filler for a particular manufacturing process.

The industries most closely concerned with utilization of fillers and the chief purposes served by the incorporation of such materials may be summarized as follows:

INDUSTRY	PURPOSE
Anti-corrosive compounds	Stabilizer; hardening in service.
Asphalt	Void filling; hardening; durability.
Cement	Void filling in asphalt, etc.
Chemical	Anti-caking agents for deliquescent crystals; support for catalysts.
Cosmetics	Absorbing agent; perfume and pigment carrier.

INDUSTRY	PURPOSE
Electrical	Stabilizer in bituminous battery box and cable compounds, etc.
Gramophone records	Homogeneity of mixture; smoothness of sound reproduction.
Linoleum	Stabilizer; resistance to wear.
Paint	Inert extender; flattening agent.
Paper	Loading agent.
Pharmaceutical preparations	Absorbing agent.
Plastics	Stabilizer of moulded articles.
Printing inks	Control of consistency; pigment carrier.
Rubber	Stabilizer; hardening of product; resistance to abrasion.
Soap	Absorbing agent; abrasive cleansing, etc.

Many substances which normally satisfy industrial requirements as fillers are also extensively employed as clarifiers, filter-aids, detergents, decolorizing agents, etc.; among these may be specifically mentioned bentonite, carbon black, diatomite and Fuller's earth.

Since the majority of fillers is essentially incoherent, artificially produced powders, the mother-substances of which are in most cases naturally occurring rocks or minerals, it is clear that their investigation and classification, especially as regards mineralogical and mechanical composition, will depend largely on modern petrographic methods.

For most practical purposes, however, the following is a list of tests normally carried out on fillers in the author's laboratories:

- (1) Specific gravity, density, voids and absorption.
- (2) Sieve analysis.
- (3) Bulk density in benzene.
- (4) Void content of dry compacted filler.
- (5) Chemical composition.
- (6) Petrological examination.
- (7) Classification of principal particle sizes by elutriation or sedimentation (micron analysis).
- (8) Computation of surface area of constituent particles where practicable (sq.cm./g.).
- (9) Practical trials with the fluid or matrix (with or without associated aggregate) with which the filler is to be incorporated.

Methods of carrying out the above determinations are sufficiently described elsewhere in this volume and reiteration is unnecessary here. Suffice it to say that in the building up of the technology of fillers, sedimentary petrography and, in particular, the methods which pursuit of this science invokes, has played an

important part and is still materially influencing the trend of research in widening the field of utility of finely ground mineral substances.

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FORENSIC SCIENCE

Criminology is defined as the *Science of Crime*. It is not in itself a term which conveys to the uninitiated the real nature and ramifications of this highly specialized and complex technology, in the same way that other sciences such as archaeology, geology, meteorology, etc., are popularly understood. The term is frequently interpreted as embracing more abstract psychological or sociological issues in the study of crime, but these do not in themselves constitute the realistic scientific approach to the problems involved.

'The development of the science of police work is comparatively recent. The scientific method was exploited in fiction, notably by Conan Doyle's masterly creation, Sherlock Holmes, as early as the latter 19th century . . .'¹

So far as applications of established petrographic methods are pertinent to the subject, it is in the realm of *Forensic Chemistry* that their functions are most fruitful. 'Forensic or legal chemistry may be defined as chemistry applied to the solution of certain problems that arise in connexion with the administration of justice. It is chemistry exercised in the service of the law'². 'All criminal investigation is concerned either with *people* or with *things*. Only people commit crimes, but they invariably do so through the medium of things'³. Thus it is fundamentally the 'things' that concern the experts in laboratories devoted to Forensic Chemistry and for that matter, to Forensic Medicine: the two are intimately interwoven in their practical functions, but it is with the former that we are here chiefly concerned. A. Lucas lists a number of separate subjects of investigation which fall to the lot of the forensic chemist whom, he says ' . . . should be not only a capable analyst, but also an experienced microscopist and photographer'⁴. Among these subjects on which the sedimentary petrographer may be and often is qualified to advise, are:

- (a) Clothing, Dust and Dirt identification.
- (b) Dust, Dirt, Glass Fragments.
- (c) Microscopy, Photography.
- (d) Infra-Red, Ultra-Violet and X-ray techniques.

In the case of (a), the petrographer is concerned chiefly with identification of dust, dirt, etc., which has been carefully extracted by traditional methods from the clothing concerned⁵. As with (b), the microscope is of paramount importance. Glass fragments adhering to clothing or other media, are diagnosed as to nature, often source, by refractive index determinations, ultra-violet examination and specific gravity tests. Little need be added regarding (c) and (d) activities, because these are largely catered for in Vol. I of this book.

Reviewing generally the modern scope of sedimentary petrography in this particular science it may be stated at the outset that the microscope is employed almost universally in examination

¹ R. F. Turner, *Forensic Science and Laboratory Technics* (Thomas, Springfield, Illinois, U.S.A.), 1949, p. IX.

² A. Lucas, *Forensic Chemistry and Scientific Criminal Investigation*, 4th. ed. (Arnold, London), 1945, p. 9.

³ P. L. Kirk, *Crime Investigation: Physical Evidence and the Police Laboratory* (Interscience, New York), 1953, p. 3.

⁴ *Op. cit.*, p. 9.

⁵ *Op. cit.*, p. 56.

of fibres, sand, dust, bullets, documents, banknotes, stains, etc. Any first-class instrument capable of giving magnifications up to 500 diameters is commonly employed, but special forms have been devised to meet particular requirements of criminal investigation departments.

Document microscopes sometimes have no stage and carry the objective and eyepiece on an arm which can be extended directly over the book or paper to be examined; magnifications ranging from 48 to 72 diameters are usually employed for this purpose. An eyepiece micrometer for the measurement of size of printed characters or width of ink lines is usually incorporated in the instrument.

Binocular stereoscopic microscopes find special application in the study of coins, bullets and cartridge cases, although with the latter what are known as 'comparison microscopes' give information of greater value¹. With this apparatus, images from two microscopes are made to appear side by side in one field of view, thus enabling minute differences in two objects to be readily distinguished. In the hands of an expert, an empty cartridge case will reveal the actual weapon from which a bullet was fired and the markings on the case caused by the striker, breech face, bullet head, extractor or ejector should prove to be distinctive.

Petrographic methods in general and the petrological microscope in particular have now taken their place in investigations of crime and in specialist hands have in more than one criminal charge played an important part in building up evidence against the suspected person. For instance, it is sometimes desirable to ascertain and prove, if possible by comparison with known material of definite origin, the source of mud, sand, dust or other inorganic matter adhering to clothes, boots, skin, hair, etc., and in such cases the most intensive researches often on minute quantities of material are prosecuted. Similarly, refuse, garbage, ashes from fire-grates, boilers and the like are subject to exhaustive tests which may and frequently do include microscopical examination and optical determination of any mineral particles isolated therefrom.

To the lay mind, mud, sand, soil, powder, dust, stains or other matter of that character, scraped off boots or clothing, even walking sticks, appears by its nature and usually meagre quantity to be most unpromising material on which indications, if not actual proof, of a person's movements may be based, but in expert hands, this information, coupled with other evidence, can be fruitful of astonishing results. It is not always a question of heavy minerals,

¹ W. R. Harrison, *Suspect Documents, Their Scientific Examination* (Sweet and Maxwell, London), 1958, p. 75.

which may or may not be recoverable, depending on the nature and quantity of material available, though as every petrographer knows it is surprising in some cases how little sediment is necessary to yield readily identifiable mineral species, if not suite, which not only betrays geological source of origin but, cautiously interpreted, helps to narrow down a possible area from which it has been derived. To quote a simple example, in some parts of the Lower Greensand outcrop, the heavy mineral suite is prolific and an amount which would comfortably adhere to a person's boots between the heel and sole would be quite sufficient, in expert hands, to betray the fact that those boots had made contact with that particular deposit.

Apart from heavy minerals, the examination of the particles themselves for grain-size, shape, authigenic coating, colour, peculiar surface features, etc., are all taken into account in any exhaustive microscopical examination for the purpose in view. When it is realized that such familiar domestic commodities as new bath sponges, certain abrasive soaps, scouring powders, washing soda, old-fashioned egg-timers, carpets, rugs, mats, and oil cloth, can often be made to yield identifiable heavy minerals, it is clear that even the most calculating criminal has to be doubly wary if he would avoid the consequences and implications of such 'dust' detection.

Naturally, this kind of evidence presents certain difficulties when given in a court of law, owing to the fact that it is necessarily extremely technical and highly specialized knowledge is required, not only in handling the data, but in adapting it to the circumstances of the case and more particularly in making it understandable to the court. On the other hand, it is seldom that learned counsel, supported by acknowledged expert witnesses, fails to present such evidence in a manner which is both convincing and comprehensible, even though a shattering cross-examination may serve to demonstrate conflicting expert opinions and the proverbial inexactitude of geological science.

From the standpoint of actually presenting such evidence, however, it is becoming increasingly common in legal work to take photomicrographs wherever possible of such material as above described and there is no doubt whatever that this course is preferable to staging demonstrations in court with a complicated petrological microscope. In this way, characteristic features can be explained to a jury far more easily by the aid of enlarged photographs constituting a series of 'exhibits' than by asking each one in turn to look through a microscope, an instrument with which the great majority of jurymen and women is totally unfamiliar and, moreover, incapable of forming any sound judgment by mere scrutiny of sediment particles.

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GLASS TECHNOLOGY

A memoir on *Sands and Rocks used in Glass-Making* by P. G. H. Boswell¹ many years ago pointed out the way in which intensive petrological study of certain sediments, in particular sands, could reveal their suitability or otherwise for this purpose and since

¹ Longmans, Green, London, 1918.

that time a mass of comparable work has been carried out on raw materials by glass technologists, who are fully alive to the uses and ramifications of the petrological microscope.

Raw materials include various high-grade silica sands, siliceous rocks containing alumina and potash, pure sandstones and quartzites, ground flint, certain quartz schists, vein quartz, feldspars, aplite, kaolin and steatite. The checking by petrographic methods of one or more of these components of the 'batch', *i.e.* the mixture which, on fusion, results in the glass product, is admittedly only a small part of a much more comprehensive technology embracing chemical and physical problems of considerable complexity. But it is none the less an essential factor in assessing the quality and behaviour of such raw materials.

In so far as sand as a raw material is concerned, P. G. H. Boswell stated that 'The ideal sand for the best glass-making is one with 100% silica and composed of angular grains all of the same size, and of the grade known as medium or fine sand. Such a perfect sand has not at present been discovered, but the ideal is approached by a few sands, including those of Fontainebleau in France (99.7% silica), Lippe in Germany (99.8% silica) and Berkeley Springs in the U.S.A. (99.65% silica).'¹

Generally, the most objectionable impurities in sands are iron-oxide, limonite or clay. Heavy minerals such as rutile, anatase, zircon, garnet, monazite, titanite, if present in any quantity, are also undesirable as they are prone to resist fusion and occur as visible blemishes in the finished glass. In the case of a crushed quartzite, vein quartz, etc., one of the objections to the use of such material is the amount of fine dust involved, which unless eliminated and thus more or less wasted, upsets the critical grading limits to which manufacturers normally work.

Examination of raw materials of the 'batch' involves both routine tests of periodical consignments of sands, etc., whether of British or foreign origin and a check on their conformity or otherwise to works' specification. Similar work is carried out on such new raw materials as may from time to time be offered. The methods employed involve essentially determination of chemical composition, mineral composition and particularly mechanical analysis; if results of these are satisfactory, practical tests on such raw material blended as may be necessary with other known components are carried out on a semi-large scale prior to translating the formula to commercial dimensions.

Apart from the use of sedimentary rocks in the manufacture of glass, it should be noted that many igneous rocks are also employed for this purpose, especially on the continent, *e.g.* basalt,

¹ *Op. cit.*, p. 48.

trachyte, phonolite, while American practice frequently favours the use of felspar, china clay and lepidolite, especially those reasonably free from iron oxide which are successfully employed in the production of colourless glass.

These applications of sedimentary petrography to raw materials by no means exhaust the potentialities of microscopical examination which, with great advantage, extends to investigation of glass both during processing and ultimately to the product itself. In this direction optical physics plays an important part. Refractive index can be a criterion of the nature of the glass body under scrutiny; isotropism and/or birefringence, assessed with the polarizing microscope, measures absence or presence of strain, its orientation, likewise any compression or tension developments. Detection and interpretation of so-called 'flaws' in glass are also part of this technique.

The principal defects studied are what are commonly known in the trade as:

- (a) Bubbles.
- (b) Cords.
- (c) Seeds.
- (d) Stones.
- (e) Striae.
- (f) Surface Blemishes or Markings.

- (a) Bubbles are usually derived from gas-filled pores and are identifiable by a normally circular shape and sometimes a relatively prominent R.I. 'Anhydrous crystalline sodium carbonate is frequently found in bubbles'¹. This substance has R.I. low, $\alpha = 1.415$, $\beta = 1.535$, $\gamma = 1.546$. Birefringence very strong, $\gamma - \alpha = 0.131$. Optically —. Bubbles are frequently found in bottle or low-grade glass; they are detrimental to plate glass, most certainly to optical glass, where absolute homogeneity is essential.
- (b) Cords are often linear defects within glass bodies, but visible because they have a different R.I. from the glass itself. 'A low-index cord is probably derived from silica. A high-index cord may come from aluminous refractories or from calcium silicate devitrification'².
- (c) Seeds are similar to bubbles in glassware and are not to be confused with 'seed crystals', sometimes introduced into super-saturated solutions to initiate crystallization.
- (d) Stones are the solid crystalline bodies sometimes found in glass and ascribable to a number of different contaminants of the batch during fusion and subsequent cooling, e.g. clay-stone, refractory grains, devitrification products. Composition of stones

¹ H. Insley and Van Derck Fréchette, *Microscopy of Ceramics and Cements* (Academic Press, New York), 1955, p. 161.

² *Ibid.*

is highly variable, dependent on conditions. Some of the commonest diagnosed are quartz, tridymite, cristobalite, corundum, β -alumina, mullite, etc.

- (e) Striae are similar to cords (*q.v.*) but may occur in parallel clusters, not necessarily as single linear blemishes. They are invariably 'inside' the glass.
- (f) Surface Blemishes or Markings are most frequently due to external reactions of glass to weathering, erosion, etc., and may often with advantage be studied microscopically in reflected light. They are not necessarily mineralogical entities although devitrification products may in certain circumstances promote such defects.

In short, the technology of glass manufacture for whatever purpose, provides the skilled microscopist with a wealth of opportunity to control (a) raw materials, (b) processing, (c) cooling phases, and (d) examination of the finished glass-type. Just as with the microscopy of ceramic and refractory bodies, it is experience that counts and the petrographer will find, in the course of his researches, that there is much in common between these synthetic materials and glass as such.

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MEDICINE (INDUSTRIAL MALADIES)

The chief avenue of medical research open to the collaboration of the sedimentary petrologist is that leading to elucidation of causes of industrial pulmonary diseases, especially the pneumoconioses. The term *pneumoconioses* embraces a group of lung diseases which arise from constant inhalation of dust in certain industrial occupations, e.g. coal mining, asbestos manufacture. The action of dust (conceived in its broadest sense) on the human lungs has been keenly debated ever since it was recognized that prolonged contact of the human being in confined spaces with certain forms of dust produces a form of phthisis which in many cases proved fatal. The subject has been one of international investigation and keen controversy between the various scientific authorities concerned and even today they are by no means agreed on the causes and, more particularly, the mechanisms of the various types of incapacitating fibrosis whose toil of human life has been so tragic.

Foremost in this field of research is silicosis, for long believed to be due exclusively to the action of finely powdered *uncombined* silica, the particles being of the order of 2μ and less in size. Asbestos dust is also a potent cause of fibroid phthisis (asbestosis) and in this case the silica is in a *combined* state as a hydrated magnesium silicate.

Dusts in any form and from whatever substance derived may

under certain conditions be deleterious to the health of the operative who is obliged to work in what is unquestionably a most unhealthy atmosphere. It is only of comparatively late years that legislation has empowered authorities to compel exclusion of dust as far as possible in factories and mines where processes tend to promote unhygienic conditions. It is true, of course, that not all dusts are injurious to human life or perhaps it would be better to say that in so far as diagnosis of pulmonary diseases is concerned, certain types of dust have so far escaped suspicion, in that no case of fibrosis has been directly traced to their incidence. This does not imply, however, that with further research it will not ultimately be found that many dusts at present not suspect will have to be placed on the black list to ensure protection of human life. 'The dictum is true that all dusts in excessive amount must be injurious, if not to the lungs, then to the upper air passages, causing atrophy of the mucous membrane with loss of vibrissae round the margin of the nose due to the catarrhal discharge set up'¹.

The petrologist's contribution to investigation of industrial dusts as conducive to phthisis is essentially that of (a) examination of the various rocks believed to be capable of causing silicosis or asbestosis; (b) examination of inorganic mineral matter recovered from silicotic or otherwise infected lungs of diseased persons; (c) reconstruction on a chemical and mineralogical basis of the mechanism by which inorganic mineral matter in a fine state of division can attack lung tissue, react chemically with lung tissue and/or fluid or can promote and aggravate conditions conducive to development of fibrosis generally and (d) in a consultative capacity he may be called upon to give expert evidence in cases of disputed claims to compensation under the various silicosis and asbestosis schemes obtaining.

As a guide to the various rocks concerned with silicosis and asbestosis, a summary of the schemes at present in force in this country and the particular industries affected is given to aid the petrologist who may be concerned either academically or professionally with this matter.

The Sandstone Industry (Silicosis) Scheme, 1931, S. R. & O., 1931, No. 346 (*superseding* S. R. & O., 1929, No. 171).

The sandstone industry for the purpose of this scheme refers to 'all processes in or incidental to the getting or manipulation of sandstone with a view to manufacture, sale or use, which are carried out on at or within the close or curtilage of any mine or quarry or at any premises worked in conjunction with a mine or quarry, wherever situate'. Sandstone includes ganister, gritstone and quartzite rocks,

¹ T. Legge, *Industrial Maladies* (Oxford University Press, London), 1934, p. 181.

but not rotten stone or natural sand. The scheme does not apply (1) to premises already covered by the Refractories Industries (Silicosis) Scheme, 1931; (2) to any premises not part of a mine or quarry where silica flour is manufactured from sandstone; (3) to any mine or quarry where sandstone is worked only occasionally and even then without the aid of explosive or mechanical power; (4) to engineers, blacksmiths, etc., working in a mine or quarry but not actually engaged in the part of the premises devoted to processes covered by the Scheme; (5) to processes for the manufacture of artificial stone except breaking, crushing and grinding of sandstone and incidental handling. See, however, *The Various Industries (Silicosis) Scheme*, 1931 (*S. R. & O.*, 1931, No. 342).

Exemption may be claimed from the scheme by employers who show that the sandstone got or manipulated at any mine, quarry or other premises does not contain more than 50% total silica.

The method approved by the Government Chemist for the determination of total silica for the purpose of this scheme is given below:

'1. A representative sample of the material shall be taken by an expert sampler. The size of the sample will depend on the homogeneity and texture of the material.

'2. The sample shall be broken into pieces of such a size that they may easily be inserted into the percussion mortar to be used in the later stages of pulverization. After it has been thoroughly mixed, the broken material must be "quartered down" to a bulk of about half a pound and then crushed in a steel percussion mortar until the whole will pass through the topmost of a battery of six sieves whose mesh is graded from 5 I.M.M.¹ (topmost sieve) to 100 I.M.M.¹ (lowest sieve). The fractions retained by each sieve after a thorough shaking shall be separately mixed, weighed, and such aliquot portions taken from each that there is obtained a final combined sample of all grades weighing not less than 10 grams. This shall be shaken again in the battery of sieves and the coarser portions crushed in the percussion mortar until the whole passes through the 100 sieve. The final powder shall be thoroughly mixed and transferred to a closed bottle. Gross particles of iron are to be removed from the powder by means of a magnet.

'3. 1 gram of the finely powdered sample is to be mixed with 4 grams of pure anhydrous sodium carbonate in a platinum crucible, the mixture being covered with a further 1 gram of the sodium carbonate. The crucible and contents shall be heated over a Teclu or Meker burner, at first gently, the heat being gradually raised to the full and so maintained for 20-30 minutes until the contents are in a state of quiescent fusion. After a final heating for 5 minutes over the blast, the crucible shall be cooled by quenching in cold water, and the fused cake removed and disintegrated by heating with water in a platinum dish. 15 millilitres of concentrated hydrochloric acid (Specific Gravity 1.15) shall then be added slowly, the dish being covered,

¹ I.M.M. signifies the scale of sieves adopted by the Institution of Mining and Metallurgy.

and after effervescence has ceased the liquid shall be evaporated to dryness over a steam bath, heating being continued until the bulk of the hydrochloric acid is removed and the deep yellow colour of the iron chloride has changed to a pale yellow. The dry mass shall be drenched with about 5 millilitres of concentrated hydrochloric acid, 100 millilitres water added, and, after solution of the soluble salts by heating, the whole shall be filtered and the silica washed first with cold water and finally with hot water until free from chlorides. The filtrate shall be evaporated again to dryness, the mass treated with hydrochloric acid and water as in the first evaporation, and the small amount of silica filtered off, and washed on a separate filter paper. The combined filter papers and silica, etc., shall be dried and ignited, finally over the blast, in a weighed platinum crucible until the weight is constant (A). A few drops of water, 5 drops of sulphuric acid (1 : 1), and 10 millilitres of pure hydrofluoric acid shall be added to the crucible and the silica volatilized by evaporation to dryness on a hot plate. The crucible and residue shall be ignited and weighed (B); the difference between (A) and (B) gives the weight of silica in the sandstone taken.

'A blank experiment must be carried out at the same time, using the same number of filter papers and similar quantities of reagents.'

Refractories Industries (Silicosis) Scheme, 1931 (S. R. & O., 1931, No. 345, superseding S. R. & O., 1919, No. 12 and S. R. & O., 1925, No. 79).

This scheme covers the getting, handling, moving, breaking, crushing, grinding, or sieving of material containing not less than 80% total silica (*e.g.* ganister) and the manipulation of such material in the manufacture of bricks or other materials containing not less than 80% total silica.

Various Industries (Silicosis) Scheme, 1931, (S. R. & O., 1931, No. 342, superseding S. R. & O., 1928, No. 975 and S. R. & O., 1930, No. 1095).

The scheme covers a variety of processes not included under the Refractories Industry and Sandstone Industry Schemes, the chief of which are given below:

- (1) Mining and quarrying in silica rock, which for the purposes of the scheme means quartz, quartzite, ganister, sandstone, grit-stone and chert, but does not include sand or rotten stone.
- (2) Drilling and blasting in silica rock incidental to the quarrying or mining of other minerals.
- (3) Sawing, planing, dressing, shaping, cutting or carving silica rock or granite or any igneous rock, but excluding kerf dressing in the case of granite and igneous rocks.
- (4) Breaking, crushing, grinding, sieving, mixing, packing, handling, removing silica rock, dried quartzose sand or some other materials of high silica content. This may include workmen engaged in laying concrete or mixing tar or asphalt macadam, should dry siliceous aggregates be employed in these processes.

- (5) Certain processes involving exposure to ground flint dust in the pottery industries.
- (6) Fettling of steel castings.
- (7) Sand blasting in foundries or metal works with quartzose sand, crushed flint or silica rock.
- (8) Underground and surface operations at tin mines.

It will be noted that the deciding factor is the geological nature of the rock, not its free or total silica content. Chemical analysis is therefore unnecessary except in so far as it may be required to confirm the geological interpretation. In such cases, the total silica is determined by the method given above and free silica by the method of A. Shaw, which is as follows¹:

Five grms. of the sample, ground to pass 60-mesh I.M.M. are mixed with 300 ml. of dilute hydrochloric acid (2.5 per cent. by vol.) and heated to boiling in a deep porcelain dish of 1,300 ml. capacity. The dish is allowed to stand for 2 hours, or until the material has settled, and the clear liquid is syphoned off. It is advisable to have a tap or pinch-cock in the syphon tube to reduce the rate of flow towards the end of the operation; if the syphon is clamped so that the end of the short limb is adjustable in the liquid, it will be found possible to remove practically the whole of the solution without disturbing the solid material. The residue is stirred with 100 ml. of water, 100 ml. of sulphuric acid (1 : 1 by vol.) are added, and the mixture is boiled, with frequent stirring, until acid fumes are freely evolved. The temperature of the solution should not rise above 200°C., and the total time of evaporation should be approximately 45 to 60 minutes. The dish is allowed to cool for 30 minutes, and its contents are diluted with a litre of water, well stirred and allowed to settle. The clear solution is syphoned off, and the residue is treated with 100 ml. of water and 100 ml. of the sulphuric acid and evaporated once more. After dilution, and settling and syphoning off the solution, the residue is neutralized with Lunge solution (100 grms. of crystallized sodium carbonate and 10 grms. sodium hydroxide in 1 litre of solution).

If the amount of acid liquid remaining in the dish is large (20 ml. or more), 50 per cent. sodium hydroxide solution should be used for neutralization, to prevent excessive dilution of the Lunge solution in the following operation. Three hundred ml. of Lunge solution are then added, and the liquid is heated to boiling, with frequent stirring. After standing for two hours the solution is syphoned off, and the residue is boiled for 5 minutes with 500 ml. of concentrated hydrochloric acid, diluted to one litre, and allowed to settle. The acid solution is syphoned off, the residue is neutralized with Lunge solution or 50 per cent. sodium hydroxide solution, 150 ml. of Lunge solution are added, and the liquid is heated to boiling. After standing for two hours, the Lunge solution is syphoned off, and the residue

¹ *The Analyst*, 59, 1934, p. 446. See also Vol. I, Ch. VIII, p. 319.

is boiled for five minutes with 200 ml. of concentrated hydrochloric acid. Two hundred ml. of water are then added, and the liquid is filtered through a Whatman No. 40 filter. The residue is transferred to the filter, washed twice with hydrochloric acid (1 : 3 by vol.) and then with water, until the washings are free from chlorides and, finally, ignited to constant weight in a tared platinum crucible. To the ignited residue are added 5 ml. of water, 5 to 10 drops of concentrated sulphuric acid and 15 ml. of hydrofluoric acid, and the resultant liquid is evaporated on a hot plate until sulphuric acid fumes are evolved. The evaporation is repeated with two further quantities of hydrofluoric acid, heating being continued during the final evaporation until sulphuric acid fumes are freely evolved, to ensure complete removal of fluorine, which would interfere with the determination of alumina in the residue. The contents of the crucible are extracted with water, and the solution is filtered. The alumina in the extract is then determined in the usual way by precipitation with ammonia, methyl red being used as indicator to avoid excess. The weight of alumina, multiplied by 5.41, gives the equivalent weight of potash felspar, and this, subtracted from the weight of the ignited residue previously determined, gives the amount of quartz or free silica in the sample.

'The above method differs from that of W. A. Selvig¹ in the use of a syphon in preference to decantation, the grinding of the sample to pass 60-mesh I.M.M. instead of 200 and the removal of silica from the residue by evaporation with hydrofluoric acid instead of by fusion with sodium carbonate and separation of the silica by evaporation to dryness with hydrochloric acid.'

Metal Grinding Industries (Silicosis) Scheme, 1931 (S. R. & O., 1931, No. 343, superseding S. R. & O., 1927, No. 380 and S. R. & O., 1930, No. 118).

The Scheme applies to processes involving the grinding of metals on grindstones composed of natural or artificial sandstone.

The Asbestos Industry (Asbestosis) Scheme, 1931 (S. R. & O., 1931, No. 344).

The inhalation of asbestos dust produces a type of fibrosis in the lungs resembling silicosis in its general features although differing in certain clinical aspects, *e.g.* the nodular structure of the fibrosis is very much less marked and tuberculosis supervenes less frequently. The disease attacks workers engaged in disintegrating raw asbestos or in manufacturing cloth and other textiles from the fibre, as well as those employed in grinding, sawing, etc., manufactured products containing substantial amounts of asbestos. Means of protection similar to those adopted for silicosis have proved successful. Provision is made in the scheme for the protection of workers in the following processes:

¹ *Carnegie Inst. Tech. Min. and Met. Invest., Bull.* 21, 1925.

- (1) Grinding, crushing, sieving, etc., of asbestos or asbestos mixture.
- (2) Manufacture of the fibre into textiles, mattresses, etc.
- (3) Sawing, turning, and grinding of manufactured articles containing asbestos (e.g. asbestos board) except those in which bitumen is used as the bonding agent.

THEORIES REGARDING THE CAUSE OF SILICOSIS

The Government regulations infer that 'free silica' (quartz) is the cause of silicosis, but some doubt has been cast on this assumption by the work of W. R. Jones¹, who concluded that the main cause is not free silica, but the fibrous silicates, such as sericite ('secondary white mica'). In the course of an inspection of the collieries in the anthracite district of the South Wales coal field, he failed to find quartz, quartzite, sandstone, gritstone and chert in some of the working places where silicosis had been contracted and it appeared probable that rocks other than the above were capable of giving rise to a silicosis-producing dust. An examination of the mineral constituents in a number of silicotic lungs revealed the fibrous hydrated silicate of aluminium and potassium (sericite) as the chief constituent present and subsequently this mineral was also found in all rock types giving rise to silicosis. The sericite detected in the silicotic lungs was in the form of minute fibres 0.5–2 μ in length and much smaller in size than the grains of quartz which were also present. The number of fibres present is therefore greatly in excess of the number of grains of quartz or of the other constituents. Sericite is frequently found in quartz-bearing rocks, but not always. W. R. Jones points out that the gold-bearing quartz of Kolar, India, contains over 90% free silica, yet silicosis is not known in the mines, whereas in South Africa where the free silica content of the gold-bearing quartz (Banket) is 80–90%, silicosis is very prevalent. On the other hand, sericite is present in abundance in the South African rock, but not in the Indian. Similarly, silicosis is common in the South Wales coalfield, but not in any other in the British Isles. This difference could not be ascribed to the nature of the quartz grains (since the South Wales sandstone grains are very similar to the Scottish) but to the fact that sericite is found in the sandstone overlying the South Wales coal measures, but not in other districts. Again, in a gold mine in Rhodesia, quartz has been drilled for twenty years without the occurrence of silicosis, whereas, on the other hand, workers engaged in crushing cryolite containing only 3% of free silica have developed symptoms. Cases, too, are known where sillimanite and other fibrous minerals have caused silicosis. W. R. Jones, therefore, considered

¹ *Journ. Chem. Met. and Min. Soc., South Africa*, 34, 1933, p. 99.

that pure quartz cannot be the principal constituent of dusts giving rise to silicosis and he regards the fibrous silicates as far more dangerous, although quartz may act in some secondary manner.

This theory is regarded by some authorities as inconclusive and it has been suggested that the difference in the prevalence of silicosis in the mines quoted may be due to the varying effectiveness of the precautionary measures rather than the presence or absence of sericite. Further, the presence of sericite in the lung is not proof that it is the cause of silicosis. It is possible for free silica to be the cause, but to be preferentially dissolved by the body fluids.

F. S. Fowweather¹ compared the amount of silica in lungs with the degree of fibrosis, but was unable to make any direct correlation. He arrived at the conclusion that the amount of silica present is not the only factor influencing fibrosis. His experiments indicate that some forms of silica are more dangerous than others and that, as is the case with other diseases, some individuals are more prone to infection than others. Pure silicosis unaccompanied by tuberculosis, bronchitis, pneumonia, etc., is found to be comparatively rare. He concluded that the soluble alkali silicates are the most dangerous forms of silica as far as giving rise to silicosis is concerned.

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¹ *Journ. Soc. Chem. Ind.*, **53**, 20, 1934, p. 448; **53**, 33, 1934, p. 713.

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MOULDING (FOUNDRY AND FURNACE) SANDS

Refractory sands for foundry and furnace purposes were originally selected, both in Great Britain and abroad, primarily by trial and error. Certain British and European moulding sands, e.g. Bunter Sand, Mansfield, Nottinghamshire, and Diestian Sand (early Pliocene) of Mons, Charleroi, etc. (the famous 'Belgian Yellow Moulding Sand'), are traditional types and long ago established optimum criteria of what was required of high silica and naturally bonded moulding sands in ferrous and non-ferrous industries.

In the First World War, European supplies of moulding sands were automatically cut to Britain and this led to an intensive investigation of actual and potential British resources of suitable refractory sands, carried out by P. G. H. Boswell at the instigation of the then Ministry of Munitions¹.

That author defined the ideal moulding sand as '... one highly refractory to heat, with maximum cohesiveness and at the same time, maximum permeability at high temperatures. It is also desirable that the sand should not dehydrate too rapidly, and therefore should have as long a life as possible. The texture of the sand is an important matter and is related to the permeability and cohesiveness ... the texture will vary according to the kind of work, and will determine the smoothness or otherwise of the surface of the castings².'

Other criteria are the nature and amount of 'bond', clay minerals or ferric hydroxide in which the available Fe_2O_3 is from 2% to 5% of the bulk sand. High silica sands should contain minimum 95%

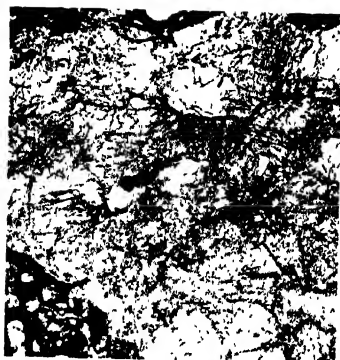
¹ *A Memoir on British Resources of Refractory Sands for Furnace and Foundry Purposes* (Taylor and Francis, London), 1918.

² *Op. cit.*, p. 81.

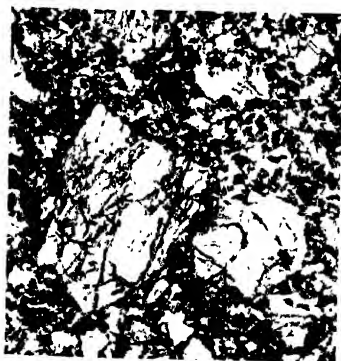
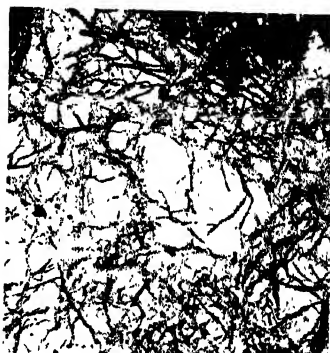
A



B



D



F



A, B. RAW MATERIALS FOR REFRACTORIES

Magnesite, Salzburg, Austria [x 22]
 Sillimanite, India [x 18.]

C-F. REFRACTORY PRODUCTS.

C. Siliceous Brick. [x 43]
 D. Silica Brick [x 43]
 E. Silica Brick [x 19]
 F. Cristobalite and Tridymite. [x 39]

silica, only very small amounts of alkalis, lime and magnesia, be well graded, and free of fine sand and silt.

More recent research has pin-pointed the vital importance of the nature of the bond in these sands, whether natural or synthetic, the latter being sand to which some specific bonding agent has been added. The chief bonding clays, whose effects on the efficiency of moulding sands have been intensively studied by R. E. Grim and F. L. Cuthbert¹, are halloysite, illite, kaolinite and montmorillonite. Of these, illite and kaolinite are probably the most durable as regards repeated moulding and casting. Halloysite and montmorillonite clays decrease in efficiency with repeated use of the sand. Although the clay bond may coat individual sand (quartz) grains, as seen under the microscope, those authors have suggested that the characteristic bonding action in moulding sands is not a case of adhesion as such, but is due to 'wedge and block' development by clay particles in contact with quartz grains; this causes them to be held rigidly in place.

Apart from an independent chemical approach, it will be clear that petrographic methods can and do play an important part in assessing the quality of moulding sands from different sources and their suitability for the particular purpose in view.

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REFRACTORY MATERIALS

Refractories may be defined as materials employed for lining furnaces, which materials must be resistant to high temperatures, changes of temperature, impact of molten metals, slag products and certain gases evolved during the firing cycle. The following are the principal types of refractories manufactured today:

¹ *Illinois State Geol. Surv., Rep. Invest.*, 102, 1945, and 110, 1946.

- (a) Basic.
- (b) Electric.
- (c) Fireclay.
- (d) Forsterite.
- (e) Silica.
- (f) Silicon Carbide.

(a) *Basic Refractories* are employed in basic open-hearth furnaces and are manufactured from magnesia-bearing materials, *e.g.* natural magnesite, brucite, or synthetic magnesia, to which are added various compounds such as silica, alumina, iron oxide, lime, etc., according to the controlling formula. The optimum firing temperature of the mix is usually around 1,500°C. and products, *e.g.* magnesite bricks, are characterized by a high degree of resistance to chemical attack and high density ('dead burned magnesia'). Chrome and chrome-magnesite bricks come into this category.

(b) *Electric Furnace Refractories* include fused alumina (mainly β -alumina), characterized by a high degree of chemical purity (over 99%); mullite (for glass-melting furnaces); and fused magnesia (for metallurgical crucibles; M.P. 2,800°C.).

(c) *Fireclay Refractories* rely, in this country, chiefly on Coal Measure fireclays, other 'flint-clays' and fireclay 'grog' (i.e. graded, broken refractory material mixed with fireclay), in manufacture of firebricks, thermal insulating bricks, blast furnace linings, boiler settings, glass-melting furnaces, etc. These are among the most variable of refractory products in post-firing mineral composition, depending on original nature of raw materials, conditions and temperature ranges of firing.

(d) *Forsterite* is magnesium silicate ($2\text{MgO} \cdot \text{SiO}_2$) with a M.P. 1,890°C. Forsterite bricks may be manufactured from natural olivine or from serpentine plus some magnesia, optimum temperature being around 1,590°C. Thin sections of these bricks may be expected to disclose the minerals olivine, magnesioferrite, occasionally hematite, and frequently periclase. Forsterite is often found in the matrix of magnesite and chrome-magnesite products.

(e) *Silica or Siliceous Refractories* are universally popular for high-temperature furnace linings, glass furnaces, pottery kilns, coke ovens, etc. The basis of these bricks is high silica sands, Coal Measure ganister, and some types of quartzite. Typical thin sections of silica bricks may be expected to reveal cristobalite, tridymite, glass, sometimes pseudo-wollastonite and calcium ferrite.

(f) *Silicon Carbide* (SiC) dissociates at 3,400°C. Silicon carbide refractories are noted for their high degree of refractoriness, thermal conductivity and resistance to chemical attack. The products normally reveal a high percentage of silicon carbide, bonded with a silica phase, *e.g.* cristobalite.

Selection of suitable raw materials for manufacture of these refractory products has long been governed by extensive laboratory tests, involving *inter alia* petrological examination of natural rocks and minerals, equally fired products, in conjunction with

other standard petrographic methods, for determining mineral composition and physical characteristics. Of raw materials, the chief are:

Alumina	Forsterite
Ball clay	Ganister
Bauxite	Graphite
Brucite	Limestone
Chalk	Magnesite
China clay	Olivine
Chromite	Quartzite
Diatomite	Sand
Dolomite	Serpentine
Fire clay	Silica rock†
Fluorite	Silicon Carbide
	Sillimanite

† Including Vein Quartz.

Each of these substances is petrologically studied in accordance with conventional procedure, either by thin section or slides of incoherent particles, whichever is the more appropriate; from this, pertinent evidence of great practical value is secured. Such investigations, if skilfully performed and properly interpreted, backed with practical knowledge of the varying processes in which one or more of those components are to be involved, never fail to throw considerable light on their ultimate behaviour on grinding, crushing, mixing and, most important of all, firing. In fact, in so far as the petrographic investigation of any final product is concerned, it is impossible to understand this completely from a petrological standpoint unless some knowledge of the raw materials initially employed has been gained.

With one or more of the above materials as basis, the following are among the more important types of products (bricks, 'shapes' and cements) manufactured in the refractories industry today:

Acid-resisting	Glass-furnace
Aluminous	Insulating
Bauxite	Insulating cements
Chrome	Magnesite
Chrome-magnesite	Magnesite cements
Chrome cements	Silica
Coke-oven	Silica cements
Dolomite	Siliceous
Firebricks	Silicon Carbide
Forsterite	Sillimanite.

Petrological examination of these products demands experience and specialized knowledge of refractory materials and manufacturing processes. In so far as microscopical examination is concerned, the technique of impregnating sections of refractories

with synthetic resin has helped enormously in their preparation and interpretation. Incidentally, it is important to note that thin sections should be much larger for this sort of work than is normally attained with ordinary sedimentary rocks¹.

Each type must necessarily be dealt with on its own merits, depending on the original constitution of the mix, the nature of the firing cycle and the degree of conversion aimed at and achieved, or otherwise. For example, with silica bricks, these are examined for degree of inversion sustained by original quartz particles, for the nature, shape, proportion and size of voids (as revealed by the coloured resin), particle size and internal structure. Relative proportions of unaltered quartz (if any), tridymite, cristobalite and associated silicates must be assessed and correlated with chemical analyses. In this work, the polarizing microscope is used, not only with thin sections, but also in the examination of fragments from crushed bricks which may sometimes with advantage be identified by refractive index (immersion) methods. V. L. Bosazza has successfully employed 'Polaroid' polarizers in conjunction with wide-field binoculars for this work².

Polished sections of refractory products, examined by incident light, as with metallurgical objects, are often of great assistance in diagnosis of their mineralogical composition.

Identification of artificial minerals is a specialized field of study and it must be admitted that in some cases of refractory products, it is impossible to determine the *whole* mass completely or to give a name to some of its components, whose complexity of composition defies expression in terms of known minerals.

In pursuing work of this character it is essential to have a large reference collection of thin sections and other relevant mounts, not only of raw materials commonly used in this country, Germany and the United States, etc., but particularly of the varying types of refractory products produced therefrom. It will also be found useful to refer to slides of minerals such as cristobalite, tridymite, mullite, etc., equally to isolated fragments of these minerals and other silicates which are continually being revealed in different types of refractory bodies, the refractive indices of which have also been previously determined.

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ROAD CONSTRUCTION AND RESEARCH

It is hardly necessary to stress the fundamental economic and social importance of roads today, not only in this country, but internationally. Civil engineering projects of highway construction and maintenance, alike airfield runways, pavings, perimeter tracks, standings, etc., call for detailed and precise specifications covering foundations, soil studies and surfacing, whether in asphalt, concrete or tarmacadam. And the fact that natural rocks enter into such specifications, many of them approved sedimentary types, is sufficient to underline the importance of the long-established petrological approach to the many problems involved in such specifications.

British Standard Specification 63 : 1951, *Single-sized Roadstone and Chippings*, includes, among others, the following sedimentary rocks used as fill, hardcore and aggregates for asphalt, concrete, etc.:

PETROLOGICAL DESIGNATION	GROUP CLASSIFICATION
Arkose	Gritstone
Breccia	Gritstone
Chert	Flint
Conglomerate	Gritstone
Dolomite	Limestone
Flint	Flint
Ganister	Quartzite
Greywacke	Gritstone
Grit	Gritstone
Limestone	Limestone
Quartzite	Quartzite
Quartzitic Sandstone	Quartzite
Recrystallized Quartzite	Quartzite
Sandstone	Gritstone

It should be noted that group classification ('trade names') tend in certain circumstances to be misleading; the correct petrological term should be used wherever possible. For example, the Gritstone group has recently come into prominence for its high resistance to polishing under traffic¹. But not all rocks contained in

¹ The Polishing of Roadstone in Relation to the Resistance to Skidding of Bituminous Road Surfacing, *Road Research Tech. Paper No. 43, D.S.I.R.*, 1958, p. 15.

this group have a high polishing coefficient and to this extent the commercial designation can be seriously misinterpreted. Also, traditionally in the quarrying industry, the word 'granite' is often used to cover rocks such as basalt, dolerite, even limestone, quartzite and greywacke in some cases known to the author; this looseness of terminology can create considerable confusion, especially where legal issues are involved¹.

The application of the petrological microscope to a study of selected sedimentary rock-types as above, has long been standard technical procedure and its practical import has been well and truly established. In particular, structures of these rocks are significant, also mineral composition, nature of cementing materials and degree of decomposition, as affecting durability in service. Generally speaking, but with exceptions, sedimentary rocks are definitely inferior to igneous rocks for first-class road construction, *i.e.* where traffic is heavy; but in many cases, such as country roads and comparatively lightly trafficked highways not involving any heavy industrial areas, carefully selected hard limestone, quartzite or flint may prove quite a satisfactory aggregate for either water-bound surfacings or with asphaltic bitumen or coal-tar binders.

In this latter connexion, certain Pre-Cambrian and Ordovician quartzites, also Carboniferous Limestones, give good results in practice, due mainly to their possessing a greater degree of consolidation, relative absence of lamination, stratification and intricate fissuring and consequent toughness under load, than geologically younger rocks of their type. For example, Pre-Cambrian Appin quartzite, Kentallen, Argyllshire, N.B.; Ordovician Stiperstones quartzite, Pontesbury, Shropshire; Carboniferous Limestone from Mendip Hills, Peak District, North Wales, to quote a few prominent examples, provide eminently satisfactory road metal. Quartzite pebbles, either in their natural state or crushed, from the Bunter Pebble Beds of the Trias, frequently make good aggregates, also form successful binders with asphaltic bitumen and sand for superimposition of non-skid, rolled asphalt wearing surfaces. Alternatively, such crushed material, like crushed flint, is used satisfactorily both for 'blinding' sprayed bitumen or tar and for precoated chippings.

Jurassic and Cretaceous limestones are usually too soft for use as aggregates *per se* except in quite local circumstances; crushed flint or natural flint gravel from the extensive gravel developments of East Anglia, Thames basin and Home Counties is nowadays more favoured, not only for use as coated macadam, but particularly for concrete. Sandstones, more particularly Palaeozoic types,

¹ See B.S. 812: 1951. Note to clause 9b, p. 15.

are in some cases sufficiently hard to be used as road aggregates, but they find more common employment in the fashioning of kerbstones and setts, for which, incidentally, much Carboniferous Limestone is used in the localities in which it is chiefly developed.

The advantage of petrological investigation of these sedimentary rock-types is not only as a means of making a selection between good and indifferent stone, but is especially valuable in aiding interpretation of results of physical and mechanical tests made on road surfacing materials, particularly in cases of failure.

In rolled asphalt composed of stone, sand and filler (B.S.594: 1958), it is often essential to examine petrologically such components, either as original individual bulk samples or as recovered from the carpet itself. The stone is determined by means of thin sections, sand and filler being examined in the usual manner. In this way, not only may the components be checked against definite provisions of the specifications, but precise sources of origin, where these are stipulated in the contract, can be ascertained and certified accordingly. In examining the finished carpet (wearing course), grouping of components into -200, 200-7 and +7 (B.S. sieves) grades, forms the basis of initial separation and examination of the total aggregate. In cases where Trinidad Lake asphalt is used, it is necessary to go further with the fine material (-200) and, apart from other tests, examine the heavy mineral residue for species which confirm evidence of its inclusion in the asphalt cement; any heavy mineral residue due to the sand or other components tends to be of coarser grade and can generally be readily eliminated and distinguished.

In specifications calling for use of 'Compressed Natural Rock Asphalt' (B.S.348: 1948), it is desirable to know whether 'approved naturally impregnated rock asphalt containing not less than 7.5% nor more than 13% of bitumen' has been employed in the manufacture of the asphalt. The raw rock, either in lump form or in powder, is submitted and examined petrologically for nature and source of origin, while tests of the finished asphalt, subsequent to laying, proceed on much the same lines. The underlying motive of such investigations is, of course, detection of adulteration with unimpregnated limestone, comparable in most respects with that technique described for the examination of building mastic asphalt based on natural rock asphalt (p. 520).

Alternative form of road-surfacing, using mastic asphalt, is that in which the mastic is prepared at the contractor's works in the usual way, compounded either of ordinary limestone aggregate or of natural rock asphalt aggregate with a given asphalt cement, the blocks being subsequently re-heated on site with the incorporation of igneous or calcareous chippings (B.S.S.1446:

1948 and 1447 : 1948). Here, again, the problem is usually to determine whether the materials specified by the engineer have indeed been exclusively used throughout the manufacture of the carpet as laid. If a sample of the carpet alone is submitted, it is not always possible to be certain that the specification has been rigidly adhered to in all respects, although adulteration, if natural rock asphalt was specified, can soon be detected; such adulteration, if proved, may lead to a very exhaustive examination of the circumstances and of materials involved in the whole contract, even some time after it has been completed. It is, however, advantageous to carry out tests collaterally with the laying of the asphalt, in which case samples of the raw materials used, both sedimentary and igneous rocks and equally the asphalt cement, are examined.

Other popular designs of asphalt road-surfacing include the use of bitumen macadam employing crushed rock or slag aggregate (B.S.1621 : 1954), bitumen macadam with gravel aggregate (B.S.2040 : 1953) and fine cold asphalt (B.S.1690 : 1950) which is extensively used for surfacing roads, footpaths, aerodrome runways, cycle tracks, playgrounds, etc.

In the modern range of tarmacadam road surfacings and dressings are specifications for dense tar surfacing (D.T.S.)¹ and tarmacadam with crushed rock or slag aggregate². Surface dressing³ with bitumen or tar is a most important feature in road maintenance and the selection of suitable blinding materials often calls for petrological examination as well as physical tests for adhesion, etc.

From the above remarks, it will readily be appreciated that applications of sedimentary petrography to the technology of modern highway construction are both many and varied and the science is becoming of ever-increasing importance as it rightly should, for its evidence on the often complicated problem of design of road foundation and surfacing materials best suited to local conditions, traffic load and available expenditure.

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The following British Standard Specifications are relevant:

B.S.63: 1951. *Single Sized Roadstone and Chippings.*

B.S.348: 1948. *Compressed Natural Rock Asphalt.*

B.S.434: 1960. *Bitumen Road Emulsions (Anionic).*

B.S.435: 1931. *Granite and Whinstone Kerbs, Channels, Quadrants and Setts.*
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B.S.594: 1958. *Rolled Asphalt, Asphaltic Bitumen and Fluxed Lake Asphalt (hot process).*

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B.S.802: 1958. *Tarmacadam and Tar Carpets (Granite Limestone and Slag Aggregate).*

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B.S.2040: 1953. *Bitumen Macadam with Gravel Aggregate.*

B.S.2542: 1954. *Recommendations for the Use of Bitumen Emulsions for Roads.*

· WATER SUPPLIES

Of all natural commodities available to mankind, water is the one most often taken for granted, a high standard of quality and adequate quantity being tacitly assumed; it takes either a fever epidemic or a severe drought to focus suddenly public attention on what is unquestionably the most vital factor in everyday life.

Purity of supply is a matter for the chemist and bacteriologist. Quantity concerns both geologist and engineer.

It is somewhat surprising to note how conventional geology of water supplies has become in this country, often largely a matter of reconnaissance, field-survey, advice as to suitable sites for wells, borings or reservoirs, the tabulation of existing bore-hole data, identification of bore-hole samples; to these must be added assessment of catchment area, rainfall, effective underground percolation and estimates of supplies at any one point. All this is part of the hydrogeologist's stock-in-trade.

The occasions, however, when porous sub-surface reservoir rocks such as sands, are studied in the same thorough manner as was done many years ago by F. H. King¹ in his classical contribution to the science on 'Principles and Conditions of the Movements of Ground Water' are relatively rare in this country; yet the data to be obtained from similar, even though far less detailed, research are invaluable in accurate assessment of supplies, direction of flow of underground water, significance of chemical composition (dissolved salts) and in solving problems of base-exchange. Time and again cases arise where cores from deep borings are vested with amazing palaeontological glamour with little, if any, consideration being given to the actual rock-types involved, which act underground as controlling factors in determining the real characteristics of the water thus made available.

Sedimentary petrology properly adapted can more than hold its own in this field; it does not matter whether the rocks are sandstones, limestones, chalk, gravel or any other favourable type; as sub-surface, natural water-reservoir rocks, they should invariably be studied at the outset of any new undertaking and petrographic methods employed to the full in determining their unseen characteristics at any particular site.

Such important British water-producing sands as the Bunter, Upper Lias, Lower Greensand and Eocene are excellent examples of deposits which have, from a purely hydrological standpoint, received close attention in everything but fundamental properties. Relevant data of this description have admittedly from time to time been accumulated by various investigators, not necessarily geologists. Only occasionally, however, is the work published; more often it lies buried in confidential reports in the archives of public water undertakings; a plea may be made here for its disinterment and appearance in technical literature. To apply the principles and practice of sedimentary petrology to problems concerning water-bearing strata is not academic, but an obvious modern method of elucidating hydrostratigraphical problems. It is

¹ *U.S. Geol. Surv., 19th Ann. Rep., 1897-98, p. 67.*

not merely a case of descriptive mineralogy. In fact, in a majority of instances, 'heavy mineral' work is of little import. On the other hand, there are many weapons in this armoury which might be used far more vigorously and with certainty of important economic results than is at present general. To illustrate such applications, a few actual cases may be quoted from the author's own experience.

(1) Two deep borings were put down on a chosen site, one situated within 50 feet of the other. The first failed owing to excessive running sand and to subsequent inability to counter it, although a supply could undoubtedly have been developed there. The second showed at comparable depth no tendency whatever to running sand and, moreover, proved a failure from the standpoint of water yield. Samples had been taken during the run of both borings and these had been carefully preserved, but casual examination had not provided any clue to the reason for such marked diversity of behaviour of the two holes.

Before proceeding further with the scheme, a critical microscopical study was undertaken of representative samples of the sands involved. In the case of No. 1 boring, the samples showed a relatively clean quartz sand of mixed grade and sub-angular particles; the absence of authigenic matter was marked and from every standpoint the sand appeared to be an ideal type for underground water percolation. In the case of the suite of samples chosen from No. 2 bore-hole, these appeared externally to be heavily limonitized quartz sands until the interior of certain of the samples was extracted, when the grains had an obvious green coating. Critical examination revealed this mineral to be ferrous carbonate, subsequently confirmed chemically and this ferrous carbonate when exposed to the atmosphere rapidly oxidized and changed colour. An examination of a large number of samples showed, in fact, that this ferrous carbonate was a copious constituent of the sands throughout the particular section from which a good supply of water had been anticipated and it was clear that its presence in such quantities in the deposit was sufficient to reduce permeability to a minimum. Deepening the boring to the base of this deposit gave no relief and the site had to be abandoned. It was therefore decided to return to the old site and, by making adequate provision to trap the mobile sand, a new bore-hole was put down from which a satisfactory supply was obtained.

(2) A bore-hole in the chalk, for some time yielding a regular supply of water of hardness 25 parts per 10^6 suddenly failed: all efforts to bring it back again proved fruitless. The boring was deepened in the hope of striking further fissures in the chalk, but this was unsuccessful, even when carried right to the base. It was, therefore, decided to bore further in the underlying Greensand. Progress of boring was controlled in this Greensand by petrological examination of samples recovered every 3 feet, with two objectives:

- (a) to reach a horizon known in the district to be productive;
- (b) to penetrate a pre-determined thickness of sandstone below this horizon to give optimum inflow into the pump.

Some 50 feet of strata were thus involved in critical examination. The samples recovered had the appearance of normal Greensand and the heavy mineral suites, where examined, were characteristic. The desired section in the Greensand was penetrated accordingly and a satisfactory supply obtained. Chemical analysis of the water from this horizon, however, revealed a surprising change in its hardness, which was now returned at 3 parts per 10⁶. It was decided to investigate the cause of such an unusual supply. Renewed petrological examination of the samples showed that the amount of glauconite present in this Greensand was unusually high and there is no doubt that the excess of this mineral had brought about a natural base-exchange whereby the calcium and magnesium salts in the water were replaced by sodium. Cases of this kind are of course well known in connexion with Greensand and also Eocene waters, but this particular instance is exceptional in the extremely high concentration of glauconite at this place.

(3) The ultimate source of water-borne sediment is often of importance in problems concerning its removal from public supply. In some instances this sediment has a decided nuisance value at the waterworks themselves, *e.g.* in wells, headings and borings, if not further field in mains and reservoirs. Headings to wells frequently get coated with iron oxide, 'foreign' silt, etc., especially where they are fed by a system of borings to deeper-lying horizons than those in which the headings are actually cut. In other cases, *positive knowledge* that water-borne sediment has been derived from a definite stratigraphical horizon can determine its elimination by suitable lining-out of the undesirable section of an existing or projected bore-hole.

Most cases of copious iron oxide deposition are due to bacteriological causes. Generally speaking, it is rare to find this in deep bore-hole supplies, providing there is no contamination from surface water; but where the gathering ground is not well protected and particularly where the rocks through which the water flows are heavily charged with iron, then given favourable conditions, iron bacteria will flourish and, unless prevented, may cause considerable trouble¹. It is in cases such as these that a knowledge of the mineral composition of the rocks involved is of paramount importance and sedimentary petrography has been used to great advantage, in conjunction with chemical and bacteriological analyses, to determine the source of such undesirable constituents in the water, whether deposited or in the form of suspended matter.

It is clear that where lithological changes are encountered in any bore-hole section, for instance where limestones and clays alternate, not only the quality of the water itself, but the nature of the sediment, if present, will be dependent to a large extent on whether the water is flowing through unlined or lined holes. The examination of such a sediment either directly or by means of its heavy mineral suite, compared with similar material of known origin in the area, has in more than one instance afforded a complete solution to problems of

¹ D. Ellis. *Iron Bacteria* (Methuen, London), 1919.

sediment contamination of water supplies which has enabled schemes to be worked out for its prevention, either at the existing site, or more particularly where new works involving similar rocks are envisaged. Cases such as the above have been worked out in the author's laboratories and it is seldom that appeal to the petrology of the sediment or solid rocks involved, coupled with intelligent interpretation of available chemical analyses, has not provided positive clues to local conditions on which satisfactory remedial measures have, in consequence, been defined.

(4) In certain problems of filtration, selection of suitable sands for this purpose is an important matter. Apart from choice of sand possessing desirable physical characteristics, its employment must be governed primarily by biological factors. For instance, it is often necessary firstly to determine the algal and/or diatomaceous and/or bacterial organisms present in the water concerned before selecting the sand and this may be taken as generally desirable procedure. Construction and particularly constitution of sand filters depend inevitably on the degree of purification aimed at. Sand filtration may be 'slow', *i.e.* natural percolation, or 'rapid', in which case a mechanical contrivance is installed periodically to clean the sand.

The British Waterworks Association has laid down a brief specification for sand (in a 2-ft. layer) which should conform to the following grading:

Circular mesh $\frac{3}{16}$ inch	All passes
Square mesh 1/25 inch	70% passes
Square mesh 1/70 inch	10% passes

The equivalent B.S. specification is as follows:

$\frac{3}{16}$ inch sieve	All passes
16 inch sieve	70% passes
44 inch sieve	10% passes

An example of the choice of a sand suitable for the above and recently worked out gave a grading as follows:

$\frac{3}{16}$ -16	30%
16-44	60%
-44	10%

Sand conforming to this specification was clean, free from silt and clay, sub-angular in grain and had a loose (initial) porosity of 42%. This example illustrates quite a simple problem of sand selection for a specific filtration purpose and it also implies the use of the microscope in determining optimum physical characteristics, quite apart from grading factors. Porosity in these cases is determined in accordance with the method given in Vol. I, Ch. VII.

It is relatively seldom that *geochemical* analyses of water, implying critical geological interpretations of the inorganic constituents revealed by chemical analysis, are undertaken in this

country; but they form a regular feature of the research work on water supplies carried out in the author's laboratories. Differentiation and/or correlation of sub-surface waters by appeal to chemical analyses is a well-known and standardized technique in most oil-field laboratories, where water sands (implying for the most part connate water) have to be identified, sealed off or otherwise taken into account. Such differentiation often has direct bearing on problems of sub-surface stratigraphical correlation. Similarly, in normal hydrogeological studies comparison of chemical analyses of waters from different known horizons in a local geological column more often than not provides the reason for particular or peculiar characteristics of the waters involved and may sometimes have definite bearing on stratigraphical problems, sub-surface structural features and lithological variations.

Other things being equal, the quality of a water from a chemical standpoint is determined primarily by its lithological environment. Changes in constitution undergone by water from the moment of its incidence on the land-surface until ultimately it reaches the site from which it is being drawn, are necessarily influenced directly by the nature of the rocks through which it flows, quite apart from any subsequent organic influence which may intervene to change fundamental characteristics; this is even more pronounced where flow is retarded, pumping decreased or suspended or in cases of underground stagnation when salinity may reach abnormal proportions; the latter condition has been well exemplified in the case of Lower Oolite water blanketed under Oxford Clay in Wiltshire, some miles in from the contact-outcrop.

In tracing the relationship between characteristics of a given water and inorganic features of its particular reservoir rock, detailed mineralogical examination of outcrop type at the gathering ground, of sub-surface samples of the corresponding deposit at site, combined with full chemical analyses of samples of the water concerned (as above) must be made. Admittedly in certain cases results are inconclusive as, for example, where sources and/or direction of flow are doubtful or multiplied or where contamination from surface water or other underground water at or near the site is manifest or probable. But it is the author's experience that in a majority of cases comprehensive chemical and petrological work of the kind herein indicated, made to supplement normal hydrogeological investigation, has everything to commend it in explaining the nature of a supply, in suggesting possibilities of new sources of supply and, particularly in the case of new works, in controlling petrologically (as well as palaeontologically where relevant) well-sinking or boring progress, so that the maximum amount of information may be given to the engineer in charge.

We conclude with an informative series of analyses in illustration of the above remarks selected from a number made in the author's laboratories on water from the Bristol district (see Table 20, pp. 594, 595); these are published by permission of the authorities concerned. In comparing them note should be taken of the rock-types involved and, incidentally, of the relevant stratigraphical horizons.

- I. Sandstones and Grits (Silurian).
- II. Sandstone (Old Red Sandstone).
- III. Limestone (Carboniferous).
- IV. Grits (Millstone Grit).
- V. Sandstone (Pennant Grit, Coal Measures).
- VI. Gypsiferous Marl (Keuper Marl).
- VII. Sand (Cotteswold Sands, Upper Lias).
- VIII. Oolitic Limestone (Inferior Oolite).
- IX. Limestone (Great Oolite).
- X. Clay (Oxford Clay).

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- See also:
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 B.S. Code of Practice. CP 310 (1952). *Water Supply.*

TABLE 20. WATER ANALYSES (RESULTS)

Geochemical Laboratories * Reference No.	I 1334B	II 1334C	III 1334D	IV 1334F
Albuminoid nitrogen	0.0126	0.0104	0.0091	0.0088
Ammoniacal nitrogen	0.0023	0.0011	0.0013	0.0023
Nitrate nitrogen	0.01	1.89	2.81	0.39
Nitrite nitrogen	Nil	Nil	Nil	Nil
Oxygen absorbed (3 hrs. at 37°C.)	0.220	0.070	0.070	0.090
Iron (Fe)	<0.002	<0.002	<0.002	<0.002
Copper (Cu)	<0.001	<0.001	<0.001	<0.001
Lead (Pb)	<0.01	<0.01	<0.01	<0.01
SALINE CONSTITUENTS				
SiO ₂	0.5	0.3	0.7	0.6
Fe ₂ O ₃ , Al ₂ O ₃	0.0	0.0	0.0	0.0
CaO	11.5	15.4	22.2	15.9
MgO	0.1	0.1	4.2	0.2
CO ₂	9.0	8.1	16.0	10.3
SO ₃	1.8	5.4	6.0	5.2
Na ₂ O	—	7.3	10.8	1.5
Chlorine in chlorides	0.8	2.7	3.7	2.2
Na ₂ O	1.6	5.1	6.3	4.7
K ₂ O	0.3	0.3	0.3	0.3
Total solids (dried at 180°C.)	26.9	49.7	77.4	41.3
HARDNESS (Soap Solution)				
Temporary	16.0	18.0	39.8	21.9
Permanent	3.9	12.0	23.0	8.1
Total	19.9	30.0	62.8	30.0
THEORETICAL COMBINATIONS				
CaCO ₃	20.6	18.4	36.3	23.4
CaSO ₄	—	8.2	4.6	6.8
CaCl ₂	—	2.6	—	—
MgCO ₃	—	—	—	—
MgSO ₄	0.3	—	5.0	0.6
MgCl ₂	—	0.3	5.0	—
Mg(NO ₃) ₂	—	—	1.4	—
Na ₂ CO ₃	—	—	—	—
Na ₂ SO ₄	2.8	—	—	1.4
NaCl	0.8	1.5	—	3.6
NaNO ₃	—	11.5	15.4	2.4
KCl	0.5	—	—	—
SiO ₂ & silicates	0.5	0.6	1.4	1.2
	25.5	43.1	69.1	39.4

EXPRESSED IN PARTS PER 100,000)

V 1122	VI 1120	VII 1241C	VIII 1388B	IX 1236E	X 1236S
0.0097	0.0079	0.0030	0.0117	0.0030	0.0062
0.0688	0.0258	0.0218	0.0018	0.0056	0.0006
0.09	0.22	0.01	0.18	0.37	0.02
Nil	Nil	Nil	Nil	Nil	Nil
0.050	0.053	0.008	0.006	0.012	0.063
—	—	—	<0.002	—	—
—	—	—	<0.001	—	—
—	—	—	<0.1	—	—
0.6	7.2	1.0	0.7	0.9	1.6
0.0	0.4	0.0	0.0	0.0	0.0
15.9	38.9	8.6	12.4	15.1	12.5
6.8	25.2	0.4	0.8	0.1	0.2
12.8	16.6	11.0	9.0	12.5	13.8
6.0	66.6	4.8	1.4	4.4	2.8
—	—	—	0.7	—	—
6.9	3.6	6.3	0.9	1.5	6.4
—	—	11.9	1.4	8.0	12.4
—	—	0.2	0.1	0.1	0.2
62.1	175.7	42.4	28.5	46.0	57.2
29.1*	39.1	16.7	21.6	29.1	23.2
16.1*	101.5	5.0	4.1	9.4	8.1
45.2*	140.6	21.7	25.7	38.5	31.3
28.4	37.3	15.4	20.5	27.0	22.3
—	43.2	—	2.3	—	—
—	—	—	—	—	—
0.6	—	0.8	—	0.2	0.4
9.0	61.8	—	—	—	—
8.2	4.8	—	1.2	—	—
—	—	—	0.7	—	—
—	—	9.2	—	1.2	9.8
—	—	8.5	—	7.8	5.0
1.3	—	5.3	—	2.5	9.1
0.6	0.3	—	0.3	—	—
—	—	0.4	—	—	0.3
0.6	7.2	1.0	1.4	2.7	1.6
48.7	144.6	41.2	26.4	41.4	48.5

* Calculated from saline constituents.

APPENDICES

In former editions of this text-book was included a limited series of determination tables, based on certain physical and optical measurements made directly under precise laboratory conditions on specific mineral grains or sections, for either diagnostic or confirmatory purposes, the aim being to expedite identification, especially in difficult cases.

In the present edition, the series has been extended to embrace all essential functions commonly sought in petrographic work and for all minerals described in Chapter I of this volume.

The author has proved by long experience in both academic and industrial environments that, following precise determinations of one or more physical properties of individual minerals, e.g. hardness, specific gravity, magnetism; or optical properties, e.g. refractive index, birefringence, isotropism, uniaxial or biaxial characteristics, optic axial angle, etc., positive diagnosis is facilitated by collective appeals to tabulated constants (or even range-values in the case of minerals of varying composition), where some system of numerical order of such constants is conveniently at hand*.

While no originality whatever is claimed for this procedure, adopted at least as long ago as 1902 by H. Miers in his classic treatise on Mineralogy†, it is believed that reproduction of the determination tables in actual use over many years in the author's laboratories, will afford a comparable degree of practical guidance to students and research workers in Sedimentary Petrography, wherever they may be operating.

Such lists have an added advantage that they are applicable to rock-minerals irrespective of origin and whether occurring as isolated grains or optically as components of thin sections. The student is, therefore, strongly recommended to study each list carefully and to make regular use of each in his practical work. By this means not only will his abilities for diagnosis be greatly and rapidly strengthened, but with constant use of these tables inherent properties of important rock-forming minerals will be gradually impressed on his mind and, incidentally, sub-consciously memorized.

In the preparation of these Appendices on mineral constants,

* Copies of these Appendices, separately mounted on cardboard for quick reference, are recommended; or a more elaborate form of card-index under each subject-heading can be devised to meet more comprehensive conditions.

† Macmillan, London.

standard works on Mineralogy* have been freely drawn upon, as also is the case with the optical functions quoted, for which latter, however, special acknowledgement is due to E. H. Larsen and H. Berman's invaluable memoir†.

* J. D. Dana, *A System of Mineralogy*, 6th ed. (Wiley, New York and Chapman and Hall, London), 1892; 7th ed., vol. I, 1944; vol. II, 1951; vol. III (in preparation). A. N. Winchell, *Elements of Optical Mineralogy*, 3rd ed. (Wiley, New York), 1933.

† The Microscopic Determination of the Nonopaque Minerals. 2nd. ed. *U.S.G.S. Bull.* 848. 1934; see also M. N. Short, Microscopic Determination of the Ore Minerals, *U.S.G.S., Bull.* 825, 1931.

APPENDIX I

MINERALS ARRANGED ACCORDING TO THEIR
SYSTEMS OF CRYSTALLIZATION

ISOMETRIC (CUBIC) SYSTEM

Allophane (?)	Grossularite	Pleonaste ⁴
Almandite	Halloysite	Pyrite
Analcite	Hercynite	Pyrope
Andradite	Maghemite	Romeite
Ceylonite ¹	Magnetite	Sodalite
Chromite	Melanite	Spessartite
Diamond	Palladium	Sphalerite
Flourite	Periclase	Spinel
Galena	Perovskite ³	Thorianite
Garnet ²	Picotite	Uraninite
Gold	Platinum	Uvarovite

¹ *Syn.* Pleonaste. ² See varieties. ³ Pseudoisometric. ⁴ *Syn.* Ceylonite.

TETRAGONAL SYSTEM

Anatase ¹	Scheelite
Autunite	Torbernite
Cassiterite	Vesuvianite ²
Chalcopyrite	Viluite ³
Rutile	Xenotime
	Zircon

¹ *Syn.* Octahedrite. ² *Syn.* Idocrase. ³ *Var.* Vesuvianite.

TRIGONAL (RHOMBOHEDRAL) SYSTEM

Ankerite	Magnesite
Benitoite	Menaccanite ²
Calcite	Phenacite
Corundum	Quartz
Dolomite	Ruby ³
Eudialite	Sapphire ⁴
Graphite	Siderite
Hematite	Tourmaline
Ilmenite ¹	

¹ *Syn.* Menaccanite. ² *Syn.* Ilmenite.

³ *Var.* Corundum. ⁴ *Var.* Corundum.

HEXAGONAL SYSTEM

Apatite	Iridosmine
Beryl	Molybdenite
Cinnabar	Nepheline
	Pyrrhotite

ORTHORHOMBIC SYSTEM

Andalusite	Fayalite (Olivine Group)
Anhydrite	Goethite ³
Aragonite	Humite (Humite Group)
Astrophyllite	Hypersthene (Pyroxene Group)
Barite	Iddingsite
Beidellite (Montmorillonite- series)	Lawsonite
Bronzite (<i>var.</i> Enstatite) (Pyroxene Group)	Ionite-Beidellite Series)
Brookite	Olivine (<i>syn.</i> Chrysolite) (Olivine Group)
Carpholite	Pseudobrookite
Celestite	Pyrophyllite
Chiastolite (<i>var.</i> Andalusite)	Sillimanite
Chrysoberyl	Staurolite
Chrysolite (<i>syn.</i> Olivine) (Olivine Group)	Steatite (<i>syn.</i> Talc) ⁴
Chrysotile ²	Strontianite
Columbite-Tantalite	Sulphur
Cordierite	Talc (<i>syn.</i> Steatite) ⁴
Diaspore	Thulite (<i>var.</i> Zoisite) (Epidote Group)
Dumortierite	Topaz
Enstatite (Pyroxene Group)	Zoisite (Epidote Group)
Eschynite	

¹ Pseudo-hexagonal. ² Dimorphous with antigorite (chlorite group) *q.v.*

³ In some instances may be tetragonal. Also amorphous.

⁴ Pseudo-hexagonal.

MONOCLINIC SYSTEM

Actinolite (Amphibole Group)	Clinochlore (Chlorite Group)
Aegirine (Pyroxene Group)	Clinozoisite (Epidote Group)
Allanite (<i>syn.</i> Orthite)	Crossite
Antigorite (Chlorite Group)	Cymatolite (<i>syn.</i> Spodumene)
Arfvedsonite (Amphibole Group)	Delessite (Chlorite Group)
Arsenopyrite	Diallage (<i>var.</i> Diopside) (Pyroxene Group)
Augite (Pyroxene Group)	Dickite (Kaolin Group)
Baddeleyite	Diopside (Pyroxene Group)
Barkevicite (Amphibole Group)	Epidote (Epidote Group)
Basaltine (Basaltic Hornblende) (Amphibole Group)	Euclase
Bastite (<i>var.</i> Antigorite) (Chlorite Group) ¹	Fuchsite
Biotite (Mica Group)	Gadolinite
Chamosite	Gastaldite
Chlorite (Chlorite Group)	Gibbsite (<i>syn.</i> Hydrargillite)
Chloritoid (Chloritoid-Ottrelite Group) ¹	Glaucophane (Amphibole Group)
	Gypsum

¹ Monoclinic (pseudo-hexagonal) or may be triclinic.

MONOCLINIC SYSTEM—*continued*

Heulandite	Ottrelite (Chloritoid-Ottrelite Group)
Hiddenite (<i>var.</i> Spodumene) (Pyroxene Group)	Penninite (Chlorite Group)
Hornblende (Amphibole Group)	Phlogopite (Mica Group)
Kaolinite (with Anauxite)	Piedmontite (Epidote Group)
Kunzite (Spodumene) (Pyroxene Group)	Pumpellyite
Lepidolite (Mica Group)	Riebeckite (Amphibole Group)
Lepidomelane (Mica Group)	Sanidine (Orthoclase Group)
Monazite	Selenite (<i>cryst.</i>) (Gypsum)
Muscovite (Mica Group)	Serpentine (Serpentine Group)
Nacrite	Sphene (<i>syn.</i> Titanite)
Nephrite (<i>syn.</i> Jade, <i>var.</i> Tremolite or Actinolite) (Amphibole Group)	Spodumene (Pyroxene Group)
Nontronite (Montmorillonite-Beidellite Series)	Steatite (<i>syn.</i> Talc) ¹
Omphacite (<i>var.</i> Diopside) (Pyroxene Group)	Stilpnomelane ²
Orthite (<i>syn.</i> Allanite)	Talc (<i>syn.</i> Steatite) ¹
Orthoclase (Felspar Group)	Thuringite
	Titanite (<i>syn.</i> Sphene)
	Tremolite (Amphibole Group)
	Triphane (<i>syn.</i> Spodumene)
	Wolframite
	Wollastonite

¹ Monoclinic (pseudo-hexagonal) or may be triclinic. ² ?Orthorhombic.

³ ?Monoclinic.

TRICLINIC (ANORTHIC) SYSTEM

Albite (Plagioclase Felspar Group)	Enigmatite
Andesine (Plagioclase Felspar Group)	Eudialite
Anorthite (Plagioclase Felspar Group)	Kyanite
Anorthoclase (Felspar Group)	Labradorite (Plagioclase Felspar Group)
Axinite	Microcline (Felspar Group)
Bytownite (Plagioclase Felspar Group)	Oligoclase (Plagioclase Felspar Group)
	Plagioclase (<i>see varieties</i>)

APPENDIX II

AMORPHOUS MINERALS

Agate	Flint	Limonite
Amber	Goethite	Opal (<i>syn.</i> Hyalite)
Chalcedony	Halloysite	Phosphorite
Chert	Jasper	Psilomelane
Collophane	Leucoxene	Pyrolusite

APPENDIX III

MINERALS ARRANGED IN ORDER OF HARDNESS (MOHS' SCALE)*

NOTE. INDEX MINERALS IN *italics*

10.0 <i>Diamond</i>	7.0 Melanite	6.0 Anatase
9.0 <i>Corundum</i>	Olivine	Andesine
Ruby	Ottrelite	Anorthite
Sapphire	Pyrope	Anorthoclase
8.5 Chrysoberyl	<i>Quartz</i>	Arfvedsonite
8.0 Beryl	Sillimanite	Arsenopyrite
Ceylonite	Spessartite	Augite
Hercynite	Spodumene	Barkevicite
Lawsonite	Staurolite	Basaltine
Picotite	Tourmaline	Benitoite
Pleonaste	6.5 Aegirine	Bronzite
Spinel	Axinite	Brookite
<i>Topaz</i>	Baddeleyite	Bytownite
7.5 Andalusite	Boehmite	Cassiterite
Beryl	Cassiterite	Chalcedony
Chiastolite	Chloritoid	Chert
Cordierite	Clinozoisite	Columbite
Euclase	Cymatolite	Crossite
Hercynite	Diaspore	Diallage
Melanite	Epidote	Diopside
Phenacite	Fayalite	Enstatite
Sillimanite	Gadolinite	Epidote
Spessartite	Hiddenite	Eudialite
Staurolite	Iridosmine	Flint
Tourmaline	Kunzite	Gastaldite
Uvarovite	Kyanite	Glaucophane
Zircon	Magnetite	Grossularite
Almandite	Marcasite	Hiddenite
Andradite	Olivine	Hornblende
7.0 Axinite	Piedmontite	Humite
Boehmite	Pyrite	Hypersthene
Cassiterite	Rutile	Ilmenite
Cordierite	Sillimanite	Iridosmine
Cymatolite	Spodumene	Jasper
Diaspore	Thorianite	Kunzite
Dumortierite	Vesuvianite	Kyanite
Epidote	Viluite	Labradorite
Gadolinite	Zoisite	Magnetite
Hiddenite	6.0 Aegirine	Marcasite
Iridosmine	Agate	Menaccanite
Kunzite	Albite	Microcline
Kyanite	Allanite	Nepheline

* Where a mineral has a hardness 'range' (e.g. Cassiterite, 6.0-7.0), it appears under each appropriate hardness number covering the range (e.g. in this case 6.0, 6.5 and 7.0).

APPENDIX III—*continued*

6.0 Oligoclase	5.5 Uraninite	4.0 Lepidolite
Omphacite	Wolframite	Limonite
Opal	5.0 Actinolite	Magnesite
<i>Orthoclase</i>	Analcite	Phlogopite
Periclase	Antigorite	Platinum
Pseudobrookite	<i>Apatite</i>	Pyrrhotite
Psilomelane	Augite	Riebeckite
Pyrite	Carpholite	Siderite
Romeite	Diallage	Sphalerite
Rutile	Diopside	Strontianite
Sanidine	Enstatite	Xenotime
Sillimanite	Eudialite	3.5 Anhydrite
Sodalite	Goethite	Ankerite
Tantalite	Hematite	Aragonite
Thulite	Hornblende	Celestite
Tremolite	Hypersthene	Chalcopyrite
Zoisite	Ilmenite	Collophane
5.5 Analcite	Kyanite	Dolomite
Anatase	Maghemite	Heulandite
Arsenopyrite	Menaccanite	Lepidolite
Augite	Monazite	Magnesite
Brookite	Palladium	Phlogopite
Carpholite	Periclase	Pyrrhotite
Chromite	Psilomelane	Siderite
Diallage	Scheelite	Sphalerite
Diopside	Titanite	3.0 Allophane
Enigmatite	Tremolite	Anhydrite
Enstatite	Wolframite	Ankerite
Eschynite	Wollastonite	Astrophyllite
Eudialite	Xenotime	Barite
Goethite	4.5 Antigorite	Bastite
Hornblende	Apatite	Biotite
Hypersthene	Kyanite	<i>Calcite</i>
Ilmenite	Palladium	Celestite
Kyanite	Platinum	Chlorite
Leucoxene	Pyrrhotite	Clinocllore
Magnetite	Scheelite	Gibbsite
Menaccanite	Xenotime	Gold
Nepheline	4.0 Ankerite	Iddingsite
Nephrite	Antigorite	Lepidolite
Periclase	Aragonite	Lepidomelane
Perovskite	Bastite	Muscovite
Psilomelane	Chalcopyrite	Nacrite
Pumpellyite	Chrysotile	Phlogopite
Romeite	Dolomite	Serpentine
Sodalite	<i>Fluorite</i>	Thuringite
Titanite	Heulandite	2.5 Amber
Tremolite	Kyanite	Autunite

APPENDIX III—*continued*

2.5 Biotite	2.0 Amber	2.0 Sulphur
Chamosite	Autunite	Thuringite
Cinnabar	Cinnabar	Torbernite
Clinocllore	Chlorite	1.5 Beidellite
Fuchsite	Clinocllore	Graphite
Galena	Delessite	Gypsum
Gold	Dickite	Molybdenite
Kaolinite	Glaucosite	Pyrophyllite
Lepidolite	Graphite	Stilpnomelane
Muscovite	Gypsum	1.0 Graphite
Nacrite	Halloysite	Molybdenite
Penninite	Kaolinite	Montmorillonite
Pyrolusite	Pyrolusite	Nontronite
Serpentine	Selenite	Pyrophyllite
Thuringite	Serpentine	Steatite (Talc)
Torbernite		

APPENDIX IV

MINERALS ARRANGED IN ORDER OF SPECIFIC GRAVITY*

1.07	Amber	2.34-2.36	Gibbsite
1.86	Allophane		Glaucosite
2.06	Sulphur		Sodalite
2.10	Opal	2.36-2.48	Glaucosite
2.14-2.18	Sodalite		Sodalite
2.18-2.20	Heulandite	2.48-2.50	Chrysotile
	Sodalite		Glaucosite
2.20-2.24	Analcite		Montmorillonite
	Glaucosite		Nacrite
	Heulandite		Nontronite
	Sodalite	2.50-2.52	Chrysotile
2.24-2.26	Analcite		Glaucosite
	Glaucosite		Iddingsite
	Graphite		Montmorillonite
	Sodalite		Nacrite
2.26-2.30	Analcite		Nontronite
	Glaucosite	2.52-2.54	Glaucosite
	Sodalite		Iddingsite
2.30-2.34	Glaucosite	2.54-2.56	Agate
	Gypsum		Chalcedony
	Sodalite		Chert

* Where a mineral has a specific gravity 'range' (e.g. Corundum, 3.95-4.10), it appears under each appropriate specific gravity value covering the range (e.g. in this case, 3.94-3.96, 3.96-3.98, 3.98-4.00, 4.00-4.06, 4.06-4.08, 4.08-4.10).

APPENDIX IV—*continued*

2·54-2·56	Flint	2·60-2·62	Nepheline
	Glaucosite		Pyrophyllite
	Iddingsite	2·62-2·64	Anauxite
	Jasper		Beryl
	Microcline		Chalcedony
	Nepheline		Chert
	Orthoclase		Collophane
2·56-2·58	Agate		Cordierite
	Anorthoclase		Flint
	Chalcedony		Glaucosite
	Chert		Iddingsite
	Cordierite		Jasper
	Flint		Kaolinite
	Glaucosite		Nepheline
	Iddingsite		Oligoclase
	Jasper		Pyrophyllite
	Nepheline	2·64-2·66	Beryl
	Orthoclase		Collophane
2·58-2·60	Agate		Cordierite
	Anorthoclase		Glaucosite
	Antigorite		Iddingsite
	Beidellite		Nepheline
	Chalcedony		Oligoclase
	Chert		Pyrophyllite
	Cordierite		Quartz
	Dickite	2·66-2·68	Andesine
	Flint		Beryl
	Glaucosite		Collophane
	Halloysite		Cordierite
	Iddingsite		Glaucosite
	Jasper		Iddingsite
	Nepheline		Pyrophyllite
	Pyrophyllite		Quartz
2·60-2·62	Albite	2·68-2·70	Andesine
	Anauxite		Beryl
	Antigorite		Collophane
	Beidellite		Glaucosite
	Chalcedony		Iddingsite
	Chert		Labradorite
	Collophane		Penninite
	Cordierite		Pyrophyllite
	Dickite	2·70-2·72	Beryl
	Flint		Calcite
	Glaucosite		Collophane
	Halloysite		Glaucosite
	Iddingsite		Iddingsite
	Jasper		Labradorite
	Kaolinite		Penninite

APPENDIX IV—*continued*

2.70-2.72	Pyrophyllite	2.80-2.82	Stilpnomelane
	Steatite	2.82-2.84	Biotite
	Stilpnomelane		Collophane
2.72-2.74	Beryl		Dolomite
	Bytownite		Eudialite
	Collophane		Iddingsite
	Glaucconite		Lepidolite
	Iddingsite		Muscovite
	Pyrophyllite		Pyrophyllite
	Steatite		Stilpnomelane
	Stilpnomelane	2.84-2.86	Biotite
2.74-2.76	Beryl		Collophane
	Collophane		Dolomite
	Glaucconite		Eudialite
	Iddingsite		Fuchsite
	Muscovite		Lepidolite
	Pyrophyllite		Muscovite
	Steatite		Phlogopite
	Stilpnomelane		Pyrophyllite
2.76-2.78	Anorthite		Stilpnomelane
	Beryl	2.86-2.88	Biotite
	Clinocllore		Collophane
	Collophane		Dolomite
	Glaucconite		Eudialite
	Iddingsite		Fuchsite
	Muscovite		Lepidolite
	Pyrophyllite		Muscovite
	Steatite		Phlogopite
	Stilpnomelane		Pyrophyllite
2.78-2.80	Beryl		Stilpnomelane
	Biotite	2.88-2.90	Biotite
	Collophane		Carpholite
	Delessite		Collophane
	Glaucconite		Dolomite
	Iddingsite		Eudialite
	Muscovite		Lepidolite
	Pyrophyllite		Muscovite
	Steatite		Phlogopite
	Stilpnomelane		Pyrophyllite
2.80-2.82	Biotite		Stilpnomelane
	Collophane		Wollastonite
	Delessite	2.90-2.92	Anhydrite
	Dolomite		Biotite
	Eudialite		Carpholite
	Iddingsite		Collophane
	Lepidolite		Eudialite
	Muscovite		Muscovite
	Pyrophyllite		Phlogopite

APPENDIX IV—*continued*

2·90–2·92	Stilpnomelane	3·08–3·10	Euclase
	Wollastonite		Eudialite
2·92–2·94	Anhydrite		Glaucophane
	Aragonite		Hornblende
	Biotite		Lawsonite
	Eudialite		Lepidomelane
	Muscovite		Phlogopite
	Phlogopite		Tourmaline
	Stilpnomelane		Tremolite
2·94–2·96	Anhydrite	3·10–3·12	Actinolite
	Ankerite		Andalusite
	Aragonite		Autunite
	Biotite		Biotite
	Eudialite		Boehmite
	Magnesite		Bronzite
	Muscovite		Chamosite
	Phlogopite		Chiasolite
	Stilpnomelane		Diopside
2·96–2·98	Anhydrite		Enstatite
	Ankerite		Glaucophane
	Biotite		Hornblende
	Eudialite		Humite
	Muscovite		Lawsonite
	Phenacite		Lepidomelane
	Phlogopite		Phlogopite
	Stilpnomelane		Spodumene
2·98–3·00	Anhydrite		Tourmaline
	Biotite		Tremolite
	Eudialite	3·12–3·16	Actinolite
	Muscovite		Andalusite
	Phenacite		Autunite
	Phlogopite		Biotite
	Stilpnomelane		Bronzite
	Tourmaline		Chamosite
3·00–3·08	Actinolite		Chiasolite
	Biotite		Crossite
	Chamosite		Diopside
	Euclase		Enstatite
	Eudialite		Glaucophane
	Glaucophane		Hornblende
	Hornblende		Humite
	Phlogopite		Phlogopite
	Tourmaline		Spodumene
	Tremolite		Thuringite
3·08–3·10	Actinolite		Tourmaline
	Autunite		Tremolite
	Biotite	3·16–3·18	Actinolite
	Chamosite		Andalusite

APPENDIX IV—*continued*

3·16-3·18	Apatite	3·22-3·24	Actinolite
	Autunite		Apatite
	Basaltine		Augite
	Bronzite		Bronzite
	Chamosite		Chamosite
	Chiastolite		Diopside
	Crossite		Enstatite
	Diopside		Hornblende
	Enstatite		Humite
	Fluorite		Phlogopite
	Hornblende		Sillimanite
	Humite		Tremolite
	Phlogopite	3·24-3·26	Actinolite
	Spodumene		Augite
	Thuringite		Axinite
	Tourmaline		Bronzite
	Tremolite		Chamosite
3·18-3·20	Actinolite		Chloritoid
	Andalusite		Diopside
	Apatite		Enstatite
	Autunite		Epidote
	Basaltine		Hornblende
	Bronzite		Humite
	Chamosite		Phlogopite
	Chiastolite		Sillimanite
	Diopside		Tremolite
	Enstatite		Zoisite
	Fluorite	3·26-3·28	Actinolite
	Hornblende		Augite
	Humite		Axinite
	Phlogopite		Bronzite
	Pumpellyite		Chamosite
	Spodumene		Chloritoid
	Thuringite		Diopside
	Tourmaline		Dumortierite
	Tremolite		Enstatite
3·20-3·22	Actinolite		Epidote
	Apatite		Hornblende
	Augite		Humite
	Bronzite		Olivine
	Chamosite		Phlogopite
	Diopside		Tremolite
	Enstatite		Zoisite
	Hornblende	3·28-3·30	Actinolite
	Humite		Augite
	Phlogopite		Axinite
	Torbernite		Bronzite
	Tremolite		Chamosite

APPENDIX IV—*continued*

3·28-3·30	Chloritoid Diopside Dumortierite Enstatite Epidote Hornblende Humite Olivine Ottrelite Phlogopite Tremolite Zoisite	3·36-3·38	Astrophyllite Augite Chamosite Chloritoid Clinozoisite Diopside Epidote Hypersthene Olivine Vesuvianite Uvarovite Zoisite
3·30-3·32	Astrophyllite Augite Chamosite Chloritoid Diopside Dumortierite Epidote Hypersthene Olivine Ottrelite Zoisite	3·38-3·40	Arfvedsonite Astrophyllite Augite Chamosite Chloritoid Diopside Epidote Hypersthene Uvarovite Vesuvianite
3·32-3·34	Arfvedsonite Astrophyllite Augite Chamosite Chloritoid Diopside Dumortierite Epidote Hypersthene Olivine Zoisite	3·40-3·42	Arfvedsonite Augite Chamosite Chloritoid Diaspore Diopside Epidote Grossularite Hypersthene Titanite Uvarovite Vesuvianite
3·34-3·36	Arfvedsonite Astrophyllite Augite Chamosite Chloritoid Clinozoisite Diopside Dumortierite Epidote Hypersthene	3·42-3·44	Arfvedsonite Augite Barkevicite Chamosite Chloritoid Diaspore Epidote Grossularite Hypersthene Riebeckite Titanite Vesuvianite
3·34-3·36	Olivine Vesuvianite Zoisite	3·44-3·46	Arfvedsonite Augite
3·36-3·38	Arfvedsonite		

APPENDIX IV—*continued*

3·44–3·46	Chamosite	3·56–3·58	Augite
	Chloritoid		Chloritoid
	Diaspore		Grossularite
	Epidote		Leucoxene
	Grossularite		Topaz
	Hypersthene	3·58–3·60	Augite
	Piedmontite		Grossularite
	Riebeckite		Leucoxene
	Titanite		Periclase
	Vesuvianite		Spinel
3·46–3·48	Augite		Topaz
	Chamosite	3·60–3·62	Kyanite
	Chloritoid		Leucoxene
	Diaspore		Periclase
	Epidote		Spinel
	Hypersthene	3·62–3·64	Kyanite
	Piedmontite		Leucoxene
	Titanite	3·64–3·66	Benitoite
3·48–3·50	Augite		Kyanite
	Chamosite		Leucoxene
	Chloritoid		Staurolite
	Diaspore	3·66–3·68	Kyanite
	Epidote		Leucoxene
	Grossularite		Staurolite
	Hypersthene	3·68–3·72	Leucoxene
	Piedmontite		Melanite
	Titanite		Staurolite
3·50–3·52	Aegirine		Strontianite
	Augite	3·72–3·74	Leucoxene
	Chloritoid		Staurolite
	Diamond	3·74–3·76	Chrysoberyl
	Grossularite		Enigmatite
	Leucoxene		Leucoxene
	Pyrope		Staurolite
	Titanite	3·76–3·78	Andradite
3·52–3·54	Aegirine		Enigmatite
	Augite		Leucoxene
	Chloritoid		Siderite
	Diamond		Staurolite
	Grossularite	3·78–3·80	Andradite
	Leucoxene		Enigmatite
	Titanite		Leucoxene
3·54–3·56	Aegirine		Limonite
	Augite		Siderite
	Chloritoid		Spessartite
	Grossularite	3·80–3·82	Enigmatite
	Leucoxene		Leucoxene
	Titanite		Limonite

APPENDIX IV—*continued*

3·80-3·82	Siderite	4·00-4·06	Goethite
	Spessartite		Leucoxene
3·82-3·84	Anatase		Perovskite
	Ceylonite		Spessartite
	Enigmatite		Sphalerite
	Leucoxene	4·06-4·08	Brookite
	Siderite		Corundum
	Spessartite		Gadolinite
3·84-3·86	Anatase		Goethite
	Ceylonite		Leucoxene
	Enigmatite		Picotite
	Leucoxene		Spessartite
	Siderite		Sphalerite
	Spessartite	4·08-4·10	Corundum
3·86-3·88	Anatase		Gadolinite
	Brookite		Goethite
	Leucoxene		Leucoxene
	Siderite		Picotite
	Spessartite		Spessartite
3·88-3·90	Anatase		Sphalerite
	Brookite	4·10-4·14	Almandite
	Hercynite		Chalcopyrite
	Leucoxene		Gadolinite
	Siderite		Goethite
	Spessartite		Leucoxene
3·90-3·94	Anatase		Spessartite
	Brookite	4·14-4·16	Allanite
	Hercynite		Almandite
	Leucoxene		Chalcopyrite
	Spessartite		Gadolinite
3·94-3·96	Anatase		Goethite
	Brookite		Leucoxene
	Celestite		Spessartite
	Corundum	4·16-4·18	Almandite
	Leucoxene		Chalcopyrite
	Spessartite		Gadolinite
3·96-3·98	Brookite		Goethite
	Corundum		Leucoxene
	Celestite		Rutile
	Leucoxene		Spessartite
	Spessartite	4·18-4·20	Almandite
3·98-4·00	Brookite		Chalcopyrite
	Corundum		Gadolinite
	Leucoxene		Goethite
	Spessartite		Leucoxene
4·00-4·06	Brookite		Psilomelane
	Corundum		Rutile
	Gadolinite		Spessartite

APPENDIX IV—*continued*

4·20-4·22	Almandite	4·52-4·58	Ilmenite
	Chalcopyrite		Pyrrhotite
	Gadolinite		Xenotime
	Goethite		Zircon
	Leucoxene	4·58-4·60	Ilmenite
	Psilomelane		Pyrrhotite
	Rutile		Xenotime
	Spessartite		Zircon
4·22-4·26	Almandite	4·60-4·70	Ilmenite
	Chalcopyrite		Molybdenite
	Gadolinite		Pyrrhotite
	Goethite		Zircon
	Leucoxene	4·70-4·74	Ilmenite
	Rutile		Molybdenite
	Spessartite		Pyrrhotite
4·26-4·28	Almandite		Romeite
	Chalcopyrite	4·74-4·76	Ilmenite
	Gadolinite		Pyrolusite
	Goethite		Pyrrhotite
	Leucoxene		Romeite
4·28-4·30	Almandite	4·76-4·78	Ilmenite
	Chalcopyrite		Pyrrhotite
	Gadolinite		Romeite
	Fayalite	4·78-4·80	Ilmenite
	Goethite		Marcasite
	Leucoxene		Pyrite
4·30-4·32	Fayalite		Pyrrhotite
	Gadolinite		Romeite
	Goethite	4·80-4·90	Ilmenite
	Leucoxene		Monazite
	Pseudobrookite		Pyrite
4·32-4·40	Chromite		Romeite
	Gadolinite	4·90-5·00	Ilmenite
	Goethite		Monazite
	Leucoxene		Pyrite
	Pseudobrookite		Romeite
	Xenotime	5·00-5·10	Monazite
4·40-4·50	Barite		Pyrite
	Chromite		Romeite
	Gadolinite	5·10-5·18	Magnetite
	Leucoxene		Monazite
	Xenotime		Romeite
4·50-4·52	Barite	5·18-5·22	Eschynite
	Chromite		Hematite
	Ilmenite		Monazite
	Xenotime		Romeite
	Zircon	5·22-5·30	Monazite
4·52-4·58	Chromite		Romeite

APPENDIX IV—*continued*

5.30-5.35	Columbite	7.40-7.60	Galena
	Romeite		Wolframite
5.35-5.40	Romeite	8.00-8.20	Cinnabar
5.40-5.90	Baddeleyite		Uraninite
5.90-6.20	Arsenopyrite	8.20-10.0	Uraninite
	Baddeleyite	11.9	Palladium
	Scheelite	14.0-19.0	Platinum
6.80-7.20	Cassiterite	19.0-21.0	Gold
7.20-7.40	Tantalite		Iridosmine
	Wolframite		

APPENDIX V

MINERALS ARRANGED ACCORDING TO THEIR MAGNETIC PROPERTIES

STRONGLY MAGNETIC

Magnetite

Pyrrhotite

MODERATELY MAGNETIC

Almandine	Crossite	Ilmenite
Andradite	Enigmatite	Lepidomelane
Arfvedsonite	Garnet	Limonite*
Augite	Gastaldite	Melanite
Barkevicite	Glauconite	Phlogopite
Basaltine	Glaucophane	Picotite
Biotite	Goethite	Sphalerite
Cassiterite*	Hematite	Stilpnomelane
Chromite	Hornblende	Wolframite
Cordierite	Iddingsite	Xenotime

WEAKLY MAGNETIC

Actinolite	Fayalite	Ottrelite
Aegirine	Gadolinite*	Penninite
Allanite	Garnet*	Piedmontite
Astrophyllite	Hercynite	Pseudobrookite
Ceylonite	Hypersthene	Pyrolusite
Chamosite	Limonite*	Riebeckite
Chlorite	Marcasite	Romeite
Chloritoid	Monazite	Scheelite
Clinocllore	Muscovite*	Serpentine*
Columbite-Tantalite	Nephrite	Spessartite
Delessite	Nontronite	Sphalerite
Diallage	Olivine	Staurolite
Diopside	Omphacite	Thuringite
Epidote	Orthite	Tourmaline

* Occasionally.

APPENDIX V—*continued*

NON-MAGNETIC

Agate	Corundum	Oligoclase
Albite	Cymatolite	Opal
Allanite	Diamond	Orthoclase
Allophane	Diaspore	Palladium
Amber	Dickite	Periclase
Analcite	Dolomite	Perovskite
Anatase	Dumortierite	Phenacite
Anauxite	Enstatite	Phosphorite
Andalusite	Eschynite	Plagioclase
Andesine	Euclase	Platinum
Anhydrite	Eudialite	Psilomelane
Ankerite	Flint	Pumpellyite
Anorthite	Fluorite	Pyrite
Anorthoclase	Fuchsite	Pyrope
Antigorite	Galena	Pyrophyllite
Apatite	Garnet	Quartz
Aragonite	Gibbsite	Ruby
Arsenopyrite	Gold	Rutile
Autunite	Graphite	Sanadine
Axinite	Grossularite	Sapphire
Baddeleyite	Gypsum	Selenite
Barite	Halloysite	Siderite
Bastite	Heulandite	Sillimanite
Beidellite	Hiddenite	Sodalite
Benitoite	Humite	Sphene
Beryl	Hyalite	Spinel
Bohemite	Iridosmine	Spodumene
Bronzite	Jasper	Steatite
Brookite	Kaolinite	Strontianite
Bytownite	Kunzite	Sulphur
Calcite	Kyanite	Talc
Carpholite	Labradorite	Thorianite
Cassiterite	Lawsonite	Thulite
Celestite	Lepidolite	Titanite
Chalcedony	Leucoxene	Topaz
Chalcopyrite	Limonite	Torbernite
Chert	Magnesite	Tremolite
Chiastolite	Microcline	Uraninite
Chlorite	Molybdenite	Uvarovite
Chrysoberyl	Montmorillonite	Vesuvianite
Chrysotile	Muscovite	Viluite
Cinnabar	Nacrite	Wollastonite
Clinocllore	Nepheline	Zircon
Clinozoisite	Nontronite	Zoisite
Collophane		

APPENDIX VI

MINERALS ARRANGED ACCORDING TO THEIR INTERMEDIATE
INDICES OF REFRACTION^{1,2}

1·406	Opal	1·565	Kaolinite
1·430	Opal	1·566	Gibbsite
1·434	Fluorite	1·568	Collophane
1·440	Opal	1·570	Antigorite
1·460	Opal	1·572	Beidellite
1·470	Halloysite	1·572	Bytownite
1·470	Allophane	1·572	Chlorite
1·483	Sodalite	1·574	Biotite
1·487	Analcite	1·574	Phlogopite
1·490	Allophane	1·575	Anhydrite
1·499	Heulandite	1·575	Autunite
1·502	Antigorite	1·576	Penninite
1·512	Chrysotile	1·577	Beryl
1·520	Halloysite	1·579	Penninite
1·523	Gypsum	1·581	Beryl
1·524	Orthoclase	1·581	Chlorite
1·525	Anorthoclase	1·581	Muscovite
1·526	Microcline	1·582	Beidellite
1·526	Montmorillonite	1·584	Anorthite
1·529	Albite	1·585	Nontronite
1·537	Beidellite	1·586	Clinochlore
1·537	Chalcedony	1·588	Pyrophyllite
1·538	Cordierite	1·589	Steatite
1·542	Halloysite	1·590	Collophane
1·542	Nepheline	1·590	Muscovite
1·543	Oligoclase	1·590	Nontronite
1·544	Quartz	1·592	Hiddenite
1·547	Cordierite	1·592	Torbernite
1·550	Chrysotile	1·594	Fuchsite
1·553	Andesine	1·597	Cordierite
1·555	Halloysite	1·598	Lepidolite
1·555	Lepidolite	1·599	Muscovite
1·558	Serpentine	1·600	Nontronite
1·561	Lepidolite	1·600	Beidellite
1·561	Phlogopite	1·600	Biotite
1·562	Chlorite	1·610	Allanite
1·562	Cordierite	1·610	Eudialite
1·562	Nacrite	1·610	Nontronite
1·563	Dickite	1·611	Muscovite
1·563	Labradorite	1·615	Stilpnomelane
1·564	Anauxite	1·616	Tremolite
1·565	Montmorillonite	1·618	Glaucanite

¹ See Ch. I, this volume, p. 17.² Compare values with Air, 1·000; Canada Balsam, 1·54 (approx.) and various R.I. liquids (Vol. I, Ch. VI, p. 248).

APPENDIX VI—*continued*

1·619	Delessite	1·681	Olivine
1·620	Nontronite	1·682	Aragonite
1·620	Topaz	1·683	Basaltine
1·623	Tremolite	1·685	Axinite
1·624	Celestite	1·685	Thuringite
1·627	Actinolite	1·686	Dumortierite
1·628	Carpholite	1·687	Riebeckite
1·628	Glauconite	1·687	Tourmaline
1·629	Wollastonite	1·689	Hypersthene
1·630	Chlorite	1·691	Hornblende
1·630	Biotite	1·695	Riebeckite
1·630	Collophane	1·698	Ankerite
1·632	Humite	1·698	Tourmaline
1·637	Barite	1·700	Arfvedsonite
1·637	Chlorite	1·701	Olivine
1·638	Glaucothane	1·702	Hypersthene
1·638	Lepidomelane	1·702	Zoisite
1·639	Andalusite	1·703	Astrophyllite
1·640	Boehemite	1·703	Zoisite
1·640	Chamosite	1·704	Augite
1·640	Thuringite	1·705	Pyrope
1·642	Hornblende	1·706	Olivine
1·643	Humite	1·707	Barkevicite
1·645	Nontronite	1·707	Pumpellyite
1·648	Biotite	1·707	Sapphire
1·649	Apatite	1·708	Vesuvianite
1·650	Iddingsite	1·715	Iddingsite
1·652	Tourmaline	1·716	Ankerite
1·653	Enstatite	1·717	Clinozoisite
1·654	Phenacite	1·718	Spinel
1·655	Euclase	1·719	Epidote
1·658	Calcite	1·720	Allanite
1·660	Chlorite	1·720	Clinozoisite
1·660	Sillimanite	1·720	Kyanite
1·666	Hornblende	1·720	Spinel
1·666	Spodumene	1·721	Xenotime
1·667	Strontianite	1·722	Chloritoid
1·669	Enstatite	1·722	Diaspore
1·670	Crossite	1·725	Hornblende
1·670	Olivine	1·726	Magnesite
1·671	Diopside	1·728	Hypersthene
1·673	Hornblende	1·729	Clinozoisite
1·674	Lawsonite	1·730	Augite
1·676	Biotite	1·730	Ottrelite
1·678	Hypersthene	1·730	Piedmontite
1·680	Allanite	1·736	Grossularite
1·680	Dolomite	1·736	Periclase
1·680	Diopside	1·739	Allanite

APPENDIX VI—*continued*

1·741	Staurolite	1·907	Titanite
1·742	Epidote	1·918	Scheelite
1·742	Pyrope	1·923	Zircon
1·748	Chrysoberyl	1·926	Zircon
1·749	Ankerite	1·936	Zircon
1·750	Ceylonite	1·940	Melanite
1·750	Spinel	1·960	Zircon
1·757	Benitoite	1·997	Cassiterite
1·757	Piedmontite	2·000	Graphite
1·760	Ceylonite	2·037	Sulphur
1·763	Epidote	2·050	Picotite
1·766	Almandite	2·060	Limonite
1·768	Corundum	2·070	Chromite
1·770	Ceylonite	2·150	Goethite
1·778	Almandite	2·160	Chromite
1·780	Ceylonite	2·190	Baddeleyite
1·780	Gadolinite	2·200	Thorianite
1·782	Piedmontite	2·220	Goethite
1·790	Ceylonite	2·250	Tantalite
1·799	Aegirine	2·260	Eschynite
1·800	Spessartite	2·290	Goethite
1·800	Enigmatite	2·320	Tantalite
1·800	Hercynite	2·320	Wolframite
1·801	Almandite	2·350	Goethite
1·801	Monazite	2·360	Wolframite
1·811	Spessartite	2·370	Sphalerite
1·814	Spessartite	2·380	Perovskite
1·830	Iddingsite	2·390	Pseudobrookite
1·830	Romeite	2·419	Diamond
1·830	Almandite	2·420	Magnetite
1·830	Siderite	2·450	Columbite
1·838	Uvarovite	2·470	Sphalerite
1·849	Siderite	2·554	Anatase
1·850	Romeite	2·586	Brookite
1·855	Siderite	2·616	Rutile
1·857	Andradite	2·720	Ilmenite
1·864	Fayalite	2·819	Cinnabar (Li)
1·870	Romeite	2·857	Cinnabar (Na)
1·875	Siderite	3·010	Hematite
1·895	Andradite	3·220	Hematite

APPENDIX VII

MINERALS ARRANGED IN ORDER OF BIREFRINGENCE

Note.—*Cf.* values for air and water 0·000; cryolite 0·001; ice 0·004 (E. S. Larsen and H. Berman *op. cit.* Table, 3, p. 35).

0·001	Eudialite	0·010	Torbernite
0·001	Gypsum	0·011	Albite
0·003	Nepheline	0·011	Chloritoid
0·003	Penninite	0·011	Dumortierite
0·004	Pseudobrookite	0·011	Hiddenite
0·005	Anauxite	0·012	Anorthite
0·005	Apatite	0·012	Arfvedsonite
0·005	Clinochlore	0·012	Barite
0·005	Gadolinite	0·012	Chamosite
0·005	Kaolinite	0·013	Hypersthene
0·005	Nepheline	0·014	Chrysotile
0·006	Cordierite	0·014	Delessite
0·006	Dickite	0·014	Wollastonite
0·006	Enigmatite	0·016	Hornblende
0·006	Muscovite	0·016	Kyanite
0·006	Nacrite	0·016	Phenacite
0·006	Riebeckite	0·016	Scheelite
0·006	Sapphire	0·016	Spodumene
0·007	Andesine	0·017	Glaucophane
0·007	Baddeleyite	0·018–0·020	Carpholite
0·007	Chalcedony	0·018–0·020	Euclase
0·007	Heulandite	0·018–0·020	Glaucosite
0·008	Anorthoclase	0·018–0·020	Zoisite
0·008	Columbite-Tantalite	0·021	Antigorite
0·008	Corundum	0·021	Barkevicite
0·008	Enstatite	0·021	Gibbsite
0·008	Microcline	0·021–0·022	Glaucosite
0·008	Oligoclase	0·021–0·022	Pumpellyite
0·008	Orthoclase	0·021–0·022	Sillimanite
0·008	Topaz	0·023	Basaltine
0·008	Vesuvianite	0·023	Glaucosite
0·009	Andalusite	0·023	Nontronite
0·009	Celestite	0·024	Allanite
0·009	Chrysoberyl	0·024	Autunite
0·009	Labradorite	0·024–0·026	Glaucosite
0·009	Quartz	0·024–0·026	Montmorillonite
0·010	Axinite	0·024–0·026	Romeite
0·010	Bytownite	0·027	Actinolite
0·010	Chamosite	0·027	Glaucosite
0·010	Clinochlore	0·027	Tremolite
0·010	Clinozoisite	0·028	Epidote
0·010	Crossite	0·028–0·029	Glaucosite
0·010	Ottrelite	0·030	Diopside
0·010	Staurolite	0·030–0·031	Glaucosite

APPENDIX VII—*continued*

0.030-0.031	Humite	0.064	Beryl
0.032	Glauconite	0.064	Biotite
0.034	Lawsonite	0.069	Stilpnomelane
0.036	Olivine	0.074	Goethite
0.040	Fuchsite	0.082	Piedmontite
0.040	Tourmaline	0.087	Iddingsite
0.042	Beidellite	0.095	Xenotime
0.042	Fayalite	0.096	Cassiterite
0.043	Augite	0.118	Lepidomelane
0.043	Muscovite	0.134	Titanite
0.044	Anhydrite	0.147	Strontianite
0.045	Aegirine	0.155	Aragonite
0.047	Benitoite	0.158	Brookite
0.047	Lepidolite	0.160	Wolframite
0.047	Phlogopite	0.172	Calcite
0.048	Diaspore	0.180	Ankerite
0.048	Pyrophyllite	0.181	Dolomite
0.049	Monazite	0.190	Ankerite
0.050	Beryl	0.191	Magnesite
0.050	Steatite	0.242	Siderite
0.051	Beryl	0.280	Hematite
0.055	Astrophyllite	0.287	Rutile
0.055	Zircon	0.288	Sulphur
0.061	Anastase	0.359	Cinnabar

APPENDIX VIII

ISOTROPIC MINERALS

Allophane	Grossularite	Pyrite
Almandite	Halloysite	Pyrope
Analcite	Hercynite	Romeite
Andradite	Maghemite	Sodalite
Ceylonite	Magnetite	Spessartite
Chromite	Melanite	Sphalerite
Diamond	Palladium	Spinel
Fluorite	Periclase	Thorianite
Galena	Picotite	Uraninite
Garnet	Platinum	Uvarovite
Gold		

APPENDIX IX

MINERALS ARRANGED IN ORDER OF OPTICAL SIGN

UNIAXIAL, POSITIVE

Benitoite	Phenacite	Scheelite
Cassiterite	Quartz	Xenotime
Cinnabar	Rutile	Zircon
Eudialite		

APPENDIX IX—*continued*

UNIAXIAL, NEGATIVE

Anatase	Dolomite	Nepheline
Ankerite	Graphite	Siderite
Apatite	Hematite	Torbernite
Beryl	Lepidomelane	Tourmaline
Calcite	Magnesite	Vesuvianite
Corundum		

BIAXIAL, POSITIVE

Albite	Diaspore	Olivine
Andesine	Dickite	Ottrelite
Anhydrite	Diopside	Penninite
Astrophyllite	Enigmatite	Perovskite
Augite	Enstatite	Piedmontite
Barite	Euclase	Pseudobrookite
Brookite	Gadolinite	Pumpellyite
Celestite	Gibbsite	Sillimanite
Chalcedony	Gypsum	Spodumene
Chloritoid	Heulandite	Staurolite
Chrysoberyl	Humite	Sulphur
Chrysotile	Iddingsite	Titanite
Clinocllore	Labradorite	Topaz
Clinozoisite	Lawsonite	Wolframite
	Monazite	Zoisite

BIAXIAL, NEGATIVE

Actinolite	Carpholite	Lepidolite
Aegirine	Chamosite	Lepidomelane
Allanite	Clinocllore	Microcline
Analcite	Clinozoisite	Montmorillonite
Anauxite	Cordierite	Muscovite
Andalusite	Crossite	Nacrite
Anorthite	Delessite	Nontronite
Anorthoclase	Dumortierite	Oligoclase
Antigorite	Epidote	Olivine
Aragonite	Fayalite	Orthoclase
Arfvedsonite	Fuchsite	Phlogopite
Axinite	Glaucinite	Pyrophyllite
Baddeleyite	Glaucophane	Riebeckite
Barkevicite	Goethite	Steatite
Basaltine	Hornblende	Stilpnomelane
Berdellite	Hypersthene	Strontianite
Biotite	Iddingsite	Thuringite
Boehmite (?)	Kaolinite	Tremolite
Bytownite	Kyanite	Wollastonite

APPENDIX X

MINERALS ARRANGED ACCORDING TO 2V (OPTIC AXIAL ANGLE)

Note.—2V is the true angle between optic axes. 2E is the measurement in air (See Appendix XI). The optic axial angle of certain minerals varies widely with composition; single values quoted below are average for normal species cited but in many cases the range of values is given.

0°–10°		20°–30°	
Beidellite	0–10	Titanite	27
Biotite	0–10	Zoisite	0–60
Chamosite	0+10		
Clinocllore	0	30°–40°	
Crossite	0+	Antigorite	27+
Delessite	0	Barite	37
Gibbsite	0–40	Brookite	30
Lepidolite	0–50	Chloritoid	30–60
Montmorillonite	0–24	Chrysotile	30–35
Orthoclase	0–70	Dumortierite	30–40
Penninite	0	Enigmatite	32
Phlogopite	3	Enstatite	31–70
Steatite	6–30	Fuchsite	40
Strontianite	7	Gibbsite	0–40
Zoisite	0–60	Iddingsite	35
		Lepidolite	0–50
10°–20°		Lepidomelane	31
Anauxite	18–31	Orthoclase	0–70
Aragonite	18	Pumpellyite	30–80
Gibbsite	0–40	Wollastonite	39
Kaolinite	10–57	Zoisite	0–60
Lepidolite	0–50		
Monazite	14	40°–50°	
Montmorillonite	0–24	Anhydrite	42
Orthoclase	0–70	Anorthoclase	45
Sillimanite	20	Barkevicite	54
Steatite	6–30	Carpholite	50
Zoisite	0–60	Celestite	51
		Chloritoid	30–60
20°–30°		Chrysoberyl	45
Anauxite	18–31	Cordierite	40–84
Antigorite	27+	Enstatite	31–70
Baddeleyite	30	Euclase	50
Chloritoid	30–60	Fayalite	47–50
Chrysotile	30–35	Gastaldite	45
Dumortierite	30–40	Glaucophane	45
Gibbsite	0–40	Lepidolite	0–50
Kaolinite	10–57	Muscovite	40
Lepidolite	0–50	Nacrite	40–90
Montmorillonite	0–24	Orthoclase	0–70
Nontzonite	26	Pseudobrookite	50
Orthoclase	0–70	Pumpellyite	30–80
Steatite	6–30	Zoisite	0–60

APPENDIX X—*continued*

50°–60°		70°–80° <i>contd.</i>	
Cymatolite	58	Astrophyllite	75 +
Diopside	59	Axinite	71
Gypsum	58	Dickite	68–80
Heulandite	52	Epidote	69–89
Kaolinite	10–57	Hornblende	62–88
Nacrite	40–90	Hypersthene	75–90
Orthoclase	0–70	Labradorite	79
Piedmontite	55–80	Nacrite	40–90
Pumpellyite	30–80	Peidmontite	55–80
Pyrophyllite	57	Pumpellyite	30–90
Spodumene	54–60	Tremolite	80
Topaz	60		
Zoisite	0–60		
60°–70°		80°–90°	
Allanite	65–70	Aegirine	81
Augite	65	Andalusite	85
Clinozoisite	66	Andesine	88
Dickite	68–80	Basaltine	83
Epidote	69–89	Boehemite	90
Hornblende	62–88	Bytownite	82
Humite	67–70	Diaspore	84
Nacrite	40–90	Epidote	69–89
Orthoclase	0–70	Gadolinite	85
Piedmontite	55–80	Hornblende	62–88
Pumpellyite	30–80	Hypersthene	75–90
Sulphur	69	Kyanite	82–84
		Lawsonite	84
		Microcline	83
		Nacrite	40–90
		Oligoclase	86
70°–80°		Olivine	86–90
Actinolite	80	Perovskite	90
Albite	74	Staurolite	88
Anorthite	77		

APPENDIX XI

MINERALS ARRANGED ACCORDING TO 2E (OPTIC AXIAL ANGLE
MEASURED IN AIR)

Note.—The optic axial angle of certain minerals varies widely with composition; single values quoted below are average for normal species cited but in other instances the range of values is given.

0°–10°		10°–20°	
Brookite	0†	Apatite	> 10*
Orthoclase	0–122	Orthoclase	0–122
Penninite	0	Phlogopite	5–70
Phlogopite	5–70	Steatite	9–48
Steatite	9–48	Strontianite	12
Zoisite	0–116	Zoisite	0–116

* Occasionally.

† For yellow-green light. Highly variable.

APPENDIX XI—*continued*

20°–30°		60°–70° <i>contd.</i>	
Anauxite	28–49	Orthoclase	0–122
Aragonite	30	Wollastonite	65
Monazite	25	Zoisite	0–116
Orthoclase	0–122		
Phlogopite	5–70	70°–80°	
Steatite	9–48	Anorthoclase	71
Zoisite	0–116	Baddeleyite	70
		Chloritoid	64–118
		Gastaldite	77
		Glaucofane	77
		Lepidolite	57–84
		Orthoclase	0–122
		Zoisite	0–116
30°–40°			
Anauxite	28–49	80°–90°	
Orthoclase	0–122	Carpholite	87
Sillimanite	33	Celestite	80
Steatite	9–48	Chloritoid	64–118
Vesuvianite	30–60	Chrysoberyl	84
Zoisite	0–116	Euclase	88
		Heulandite	82
		Lepidolite	57–84
		Orthoclase	0–122
		Zoisite	0–116
40°–50°			
Anauxite	28–49	90°–100°	
Antigorite	43	Chloritoid	64–118
Nontronite	42	Gypsum	95
Orthoclase	0–122	Orthoclase	0–122
Steatite	9–48	Pyrophyllite	98
Vesuvianite	30–60	Zoisite	0–116
Zoisite	0–116		
50°–60°			
Brookite	55*	100°–120°	
Dumortierite	52–70	Barkevicite	102
Enigmatite	59	Chloritoid	64–118
Enstatite	52+	Cymatolite	108
Lepidolite	57–84	Diopside	110
Lepidomelane	52	Orthoclase	0–122
Orthoclase	0–122	Spodumene	108
Titanite	52	Zoisite	0–116
Vesuvianite	30–60		
Zoisite	0–116	120°–140°	
60°–70°		Albite	134
Anhydrite	68	Augite	136
Barite	63	Clinozoisite	138
Chloritoid	64–118	Humite	132
Dumortierite	52–70	Orthoclase	0–122
Fuchsite	66		
Iddingsite	62		
Lepidolite	57–84		
Muscovite	68		

* For red light. Highly variable.

APPENDIX XI—*continued*

	140°–160°		160° +
Axinite	156	Anorthite	163
Cordierite	151	Labradorite	172

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The following references to the literature on Sedimentary Petrography incorporate all those published in the third edition (1940) and many others which have been added up to and including 1958. This Bibliography is not intended to be exhaustive, the titles being selected as far as possible to cover the various phases of petrographic work dealt with in the text of both Volumes I and II. Selected bibliographies will also be found at the conclusion of chapters or sections of chapters devoted to specialized aspects of the subject in both volumes. These are intended to supplement the information given in this main Bibliography and should be consulted accordingly.

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